

ABSTRACT

Title of dissertation: **SHARP-FIN-INDUCED HYPERSONIC
SHOCK-WAVE/BOUNDARY-LAYER
INTERACTIONS**

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A series of experimental campaigns were conducted to study the hypersonic shock-wave/boundary-layer interaction (SWBLI) generated by a sharp fin on a flat plate. A campaign focusing on the case of a transitional incoming boundary layer was investigated in the HyperTERP reflected-shock facility. This campaign demonstrated the viability of fast-response temperature-sensitive paint as a diagnostic technique for a facility of this scale and also showed the value of a plan-view schlieren made possible through flush-mounted windows. Results showed the presence of quasi-conical symmetry for this transitional SWBLI and a significant level of unsteadiness in the inception region and near the separation line. Schlieren results showed the ability to identify the line of upstream influence from a power spectral density analysis of the plan-view data.

The new high-temperature Ludwig tube (HTLT) facility at the University of Maryland, College Park was characterized for both Mach-6.25 and Mach-8 configurations. The Mach-6.25 Pitot rake survey showed test times of ~ 100 ms with a core flow diameter ≥ 184 mm. In the Mach-6.25 configuration, the facility is able to generate Reynolds numbers of up to $44 \times 10^6 \text{ m}^{-1}$. The Mach-8 Pitot rake survey showed test times of 40-80 ms with a

core flow diameter of roughly 300 mm with the ability to reach Reynolds numbers of $13 \times 10^6 \text{ m}^{-1}$. These measurements were corroborated by schlieren imaging and Femtosecond Laser Electronic Excitation Tagging velocimetry. Neither the Pitot rake surveys nor the velocimetry measurements showed any evidence of the presence of a wake generated by the piston system through which the facility operates.

Subsequently, an experimental campaign was conducted in the HTLT facility investigating the fin-induced SWBLI in the case of a turbulent incoming boundary layer. Heat-flux distributions show the progression through different flow regimes and the presence of quasi-conical symmetry. At higher interaction strengths, the appearance of a tertiary peak and secondary trough in the heat flux may be indicative of the onset of secondary separation and reattachment. A survey over the parameter space shows an influence of both Reynolds number and interaction strength on quantities such as maximum surface heating and the spatial distribution of the heat flux. High-speed plan-view schlieren imaging shows broadband elevated energy levels between the shock wave and the fin surface.

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by

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Nomenclature

α	Angle of attack
β	Shock-wave angle
$\beta_{q_{Max}}$	Angle of line of maximum heat flux
β_{UI}	Angle of line of upstream influence
Δ	Standard error for prediction
δ_ℓ	Theoretical laminar boundary-layer thickness
γ	Ratio of specific heats
γ_p	Ratio of specific heats under perfect gas assumptions
ρ	Density
ρ_∞	Freestream density
τ	Dummy integration variable
θ	Angular coordinate
θ'	Normalized angular coordinate
θ_v	Characteristic vibrational temperature
c	Specific heat
d_c	HTLT cold-section diameter
d_h	HTLT hot-section diameter
f	Frequency
k	Thermal conductivity
M	Mach number

M_∞	Freestream Mach number
M_n	Normal component of Mach number
p	Pressure
p_0	Stagnation pressure
p_∞	Freestream pressure
p_{Tube}	HTLT charge-tube pressure
$q(t)$	Surface heat-flux rate
q_{Max}	Maximum heat flux
r	Radial distance
R_1	Primary reattachment
R_2	Secondary reattachment
Re	Reynolds number
Re_m	Unit Reynolds number
S_1	Primary (incipient) separation
S_2	Secondary separation
T	Temperature
t	Time
T_0	Stagnation temperature
T_{cold}	HTLT cold-section temperature
T_{hot}	HTLT hot-section temperature
T_{Tube}	HTLT charge-tube temperature
U_∞	Freestream velocity
UI	Upstream influence
x	Horizontal (streamwise) coordinate
x'	Horizontal coordinate in fin-aligned frame

y Vertical (spanwise) coordinate
 y' Vertical coordinate in fin-aligned frame
 FLEET Femtosecond laser electronic excitation tagging
 HTLT High-temperature Ludwig tube
 HyperTERP Hypersonic Tunnel for Educational and Research Purposes
 PEEK Polyether ether ketone
 PSD Power spectral density
 Ruphen Ruthenium tris(1,10-phenanthroline) dichloride
 SPOD Spectral proper orthogonal decomposition
 STD Standard deviation
 SWBLI Shock-wave/boundary-layer interaction
 TSP Temperature-sensitive paint
 VCO Virtual conical origin
 VCO_q Virtual conical origin based on heat-flux distribution

Chapter 1: Introduction

1.1 Motivation

The study of hypersonic aerodynamics is an immensely interdisciplinary and difficult one. A large part of this difficulty arises from the range of scales that hypersonic flight encompasses. At the largest scale, the design of a flight path for a high-speed vehicle will include considerations of meteorology, atmospheric science, and possibly even orbital mechanics if the craft in question is experiencing reentry. Juxtaposed to this are the microscopic effects of the fluid as it interacts with the surface of the vehicle itself: accounting for phenomena such as surface ablation and aerodynamic heating requires an incorporation of physical chemistry and elements of quantum mechanics to accurately model the dynamics between the fluid molecules and vehicle body. This does not even include all of the classical problems that arise when designing conventional low-speed aircraft such as flight dynamics, controls, performance, and so on. Moreover, these classical problems can become substantially more challenging in the hypersonic regime, and quantities that may be relegated to insignificance for low-speed aircraft may become limiting design parameters in the configuration of a hypersonic vehicle.

Hypersonic flight has been studied for decades; however, due to this complexity and the extreme environments in which it takes place, it still remains an active area of research. Indeed, even gathering experimental data on these flows can prove exceptionally challenging. Since there are still many unanswered questions around the dynamics of hypersonic flight,

flight testing can prove risky and oftentimes prohibitively expensive. Ground-testing facilities, such as wind tunnels, provide an alternative through which data can be gathered at a lower risk and cost, but they are not without their trade-offs in that they typically produce a less realistic flow environments or only one portion of the flight envelope. Computational fluid dynamics offer another approach to gathering data on these flowfields; however, due to an incomplete theoretical understanding of the relevant physics and the computational expense of these simulations, they are likewise limited by the model implemented and the machine resources available.

With obstacles like these ever-present in the study of hypersonic aerodynamics, many of the challenges to achieving practical hypersonic flight seemed insurmountable and interest in the topic waned over the decades. Nonetheless, in recent years, there has been a resurgence in the interest in hypersonics. This has been driven by both defense and commercial forces: the defense industry views hypersonic systems as a key part of its future strategic defense; several industry leaders have expressed interest in developing commercial hypersonic flight in the coming decades. With the renewed and burgeoning interest in hypersonic flight, the investigation into its fundamental flow physics is once again at the forefront of research. Moreover, with the growing number of real-world applications of hypersonic technologies, it appears that this area of research is here to stay, and a better understanding of these problems is imperative to the proliferation of hypersonics and to the fulfilling of these goals.

1.2 Shock-wave/boundary-layer interactions

There are numerous aspects of high-speed aerodynamics that still lack a comprehensive understanding, one of these being that of shock-wave/boundary-layer interactions. Because these interaction can occur in a variety of different forms and will be specific to a given

vehicle, it can be useful to consider them in simplified canonical forms. Several of these canonical SWBLI configurations can be seen in Fig. 1.1. By gaining an understanding of these simplified geometries, insights can be made into their analogous counterparts on a given hypersonic vehicle.

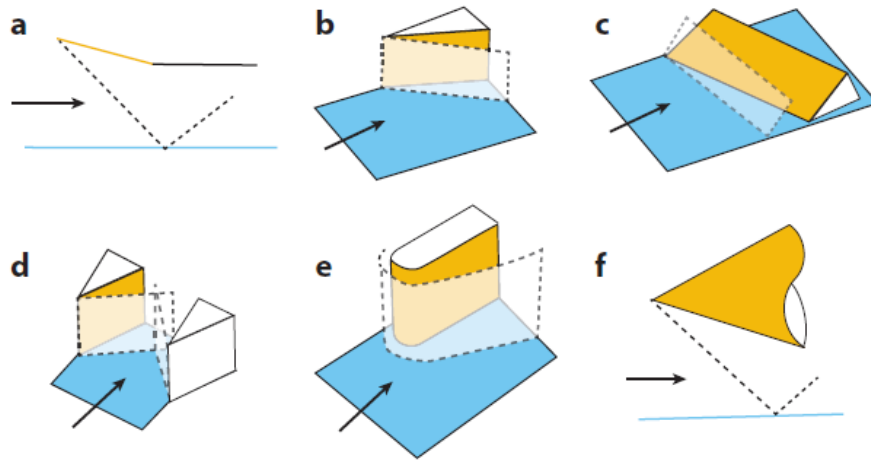


Figure 1.1: Canonical shock-wave/boundary-layer-interaction configurations: (a) impinging shock, (b) sharp fin, (c) swept compression ramp, (d) double fin, (e) blunt fin or cylinder on plate, (f) cone above plate. From Gaitonde and Adler [1].

The importance these interactions is pervasive throughout the entirety of the vehicle design process. The sharp fin (Fig. 1.1a), swept ramp (c), and blunt fin (e) configurations are very similar to control surfaces such as ailerons or rudders. The impinging shock (a and f) and double-fin (d) may be crucial design considerations for the inlet of an air-breathing propulsion system. Examples of where geometries such as these may be relevant can be seen in Fig. 1.2, which highlights flowfield locations on a generic hypersonic aircraft where specific interactions may be present. However, it is not only the ubiquity of these interactions which make them such an important design consideration but their effects as well.

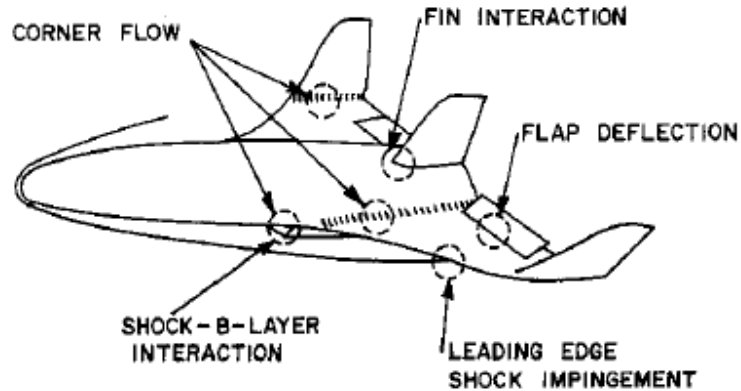


Figure 1.2: SWBLIs on a high-speed aircraft. From Korkegi [2].

In hypersonic flight in particular, many of the limitations of the aircraft system are imposed by thermal loads and materials limitations. When SWBLIs occurs, they can often exacerbate these exact problems: an shock wave impinging upon the surface of an aircraft can cause high heating loads at that location; a SWBLI may cause boundary-layer separation and the separated region can generate low-frequency unsteadiness, which can resonate with the natural frequency of the structure and lead to structural fatigue and failure; the interaction may change the boundary-layer transition location which can drastically increase aerodynamic heating over downstream portions of the craft. The list of potential complications that can arise from SWBLIs is extensive and nuanced; therefore, a more comprehensive study of these flowfields is necessary.

The specific SWBLI that will be focused upon in the current study is that of the sharp fin attached to a flat plate (Fig. 1.1b). This canonical geometry is particularly representative of a rudder or other vertical control surface on a hypersonic vehicle. A survey of the characteristic flow features of this SWBLI and the current understanding of this interaction, as well as some of the open areas of research and the scope of the current work, is thus given below.

1.3 Historical studies and canonical features

One of the first studies focusing specifically on the sharp-fin/flat-plate configuration was that of McCabe [10] in 1966. Over the subsequent decades, the problem was studied with varying degrees of focus by many others, sometimes being the only geometry considered and other times being part of campaigns studying a wider breadth of SWBLIs. Although many of the canonical components of the flowfield were identified individually by different investigations over this period, a comprehensive physical model of the sharp-fin/flat-plate configuration with a turbulent incoming boundary layer was finally compiled by Alvi and Settles [5] in 1992. One of the important behaviors discussed in Alvi and Settles' seminal work is the nature of flowfield evolution as the strength of the interaction increases. Despite this evolution, there are several characteristic features of the SWBLI that are typically present at most interaction strengths, which are shown in the sketch by Mears et al. [3] in Fig. 1.3.

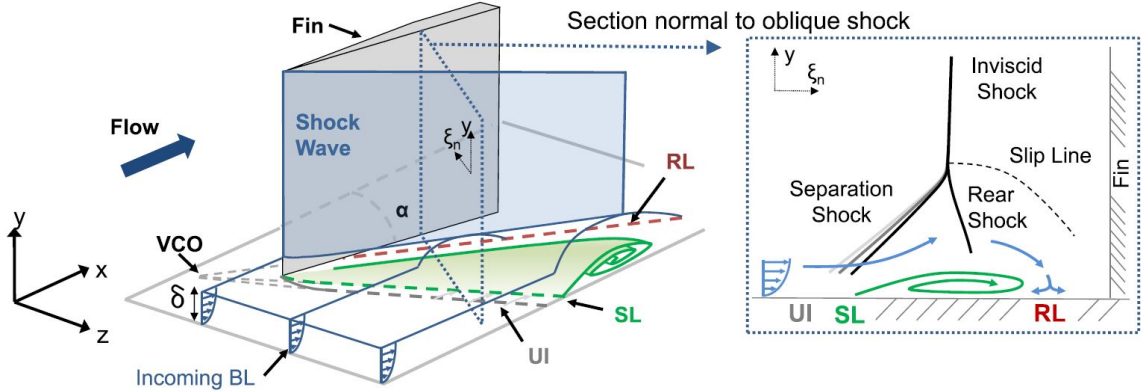


Figure 1.3: Sketch of primary flow features; adapted from Mears et al. [3].

To understand the development of these flow structures, it is convenient to consider a two-dimensional cross-section (the $\xi_n - y$ plane in Fig. 1.3) of the SWBLI which is orthogonal to the shock wave and plate surface. This shock wave, which in the inviscid case is planar, extends from the top of the fin down into the boundary layer. The interaction

with the viscous boundary layer causes the shock wave to bifurcate and form a λ -shock structure. The leg of the λ -shock that reaches upstream is known as the separation shock; the leg that reaches downstream is known as the rear shock. As the undisturbed incoming boundary layer approaches the interaction, it is first affected by the separation shock at the point of upstream influence (UI). This location is important because it marks the farthest outboard/angular extent of the SWBLI. A short distance downstream, the separation shock, which induces a large adverse pressure gradient, causes the boundary layer to undergo separation (SL). Separation at this location in the interaction is known as primary or incipient separation and is often denoted S_1 , a distinction that will become important later when separation may occur at other locations within the interaction as well. This incipiently separated boundary layer subsequently forms an open helical vortex (sketched in green) above the surface of the plate. Closer to the fin, the boundary layer reattaches to the plate surface (RL) in what is known as primary reattachment and denoted R_1 . Additionally, due to the difference in shock strengths above and below the bifurcation point of the shock wave, a different velocity is imparted by the shock system above and below this point, forming a slip line. When considered in the $\xi_n - y$ plane, the locations of farthest upstream influence, separation, and reattachment correspond to points; however, when the full three-dimensional flowfield is considered, the respective loci of these points form lines which, when extrapolated upstream, all converge at a point known as the virtual conical origin (VCO), about which the flowfield exhibits a quasi-conical symmetry. This symmetry makes spherical coordinates centered about the VCO the natural framework in which to study this problem. It is important to note that this symmetry is only observed in the far downstream region. Near the fin leading edge, the SWBLI has not yet fully developed and the quasi-conical symmetry is not observed; this upstream portion of the flowfield is known as the inception region. Using this terminology, some of the more nuanced characteristics of this SWBLI can be discussed.

As mentioned, an important aspect of this SWBLI is its progression through a series of flow regimes as the strength of the interaction changes. Some of the earliest work identifying the presence of different flow structures as the fin angle was increased was performed by Korkegi [11], who noted the occurrence of secondary separation and reattachment. However, many also point to the work of Zheltovodov et al. [4] in identifying the surface flow features of the different flow regimes, which are reproduced in Fig. 1.4.

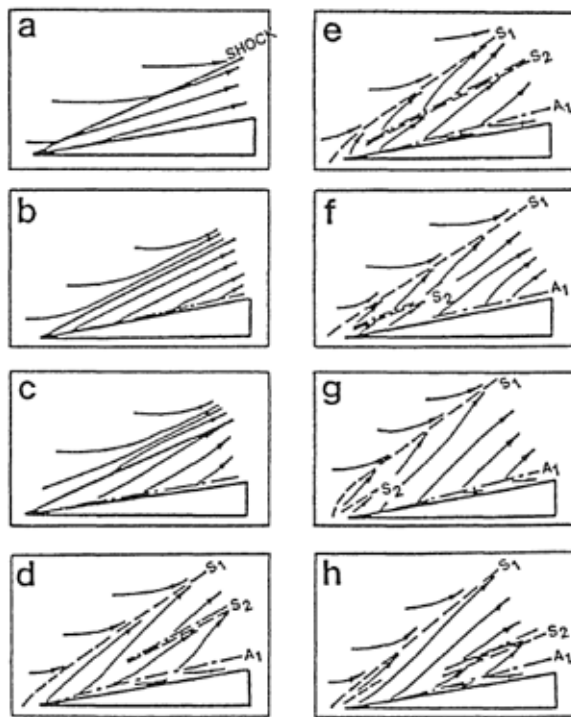


Figure 1.4: Surface flow features for different flow regimes. From Zheltovodov et al.[4]

These surface flow patterns correspond to the flow features later visualized by Alvi and Settles [5, 12]. Because frequent reference will be made to these flowfield sketches, they are included in Appendix A. From these sketches, the features that were discussed in relation to Fig. 1.3 can be seen in more detail; however, it is also clear that there are other flow structures present. In particular, one can see, for moderate interaction strengths, the indications of a secondary region of separation inside the primary separation bubble, first identified by Korkegi [11]. This secondary separation is occurring within what is

called the reverse flow region (so called since it is moving in the opposite direction of the incoming boundary layer) underneath the primary separation bubble that forms after the boundary layer reattaches at R_1 . At even higher interaction strengths, the reverse flow region is actually accelerated to supersonic speeds and can terminate in a small λ -shock system as is shown in Fig. A.1f. Looking between the primary separation bubble and the slip line, it can be seen that the flow which is not entrained by the primary separation vortex is turned and forms a jet that impinges upon the plate surface at the location of primary flow reattachment [13]. This turning of the flow is accomplished via a series of Prandl-Meyer expansion fans which also form compression waves as they reflect off the slip line. These compression wave coalesce into "shocklets" and, at high enough interaction strengths, can form a "normal shock" that terminates the supersonic flow of the jet before it impinges upon the plate surface [12].

Because of the dependence of the characteristic flow features on the strength of the interaction, it is important to define a parameter which governs the strength of the interaction. Settles and Lu [14] found that a suitable parameter is the normal component of the incoming Mach number, defined for this SWBLI as $M_n = M_\infty \sin \beta$. Using this governing parameter, the different structures seen can be assigned to different flow regimes that are determined by the value of M_n . This is shown in Fig. 1.5, which shows primary separation occurs at $M_n = 1.2$, secondary separation at $M_n = 1.5$, "normal shock" formation at $M_n = 1.9$, and finally supersonic reverse flow at $M_n = 2.1$.

Despite these variations in the canonical features of the flowfield as M_n is changed, for all of these interaction strengths the flowfield still obeys quasi-conical symmetry. That is, when viewed in a conical coordinate system with an appropriate origin, the features that vary azimuthally should collapse. The appropriate origin for this coordinate system is the virtual conical origin. As previously mentioned, this location is determined by tracing features such as the separation and reattachment lines, the line of upstream influence, and an

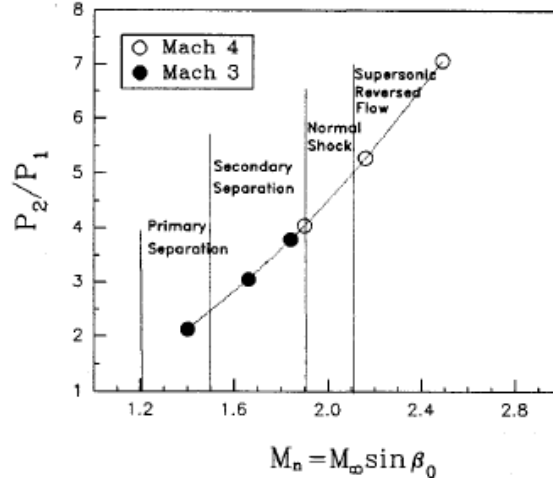


Figure 1.5: Flow regimes and their dependence on M_n . From Alvi and Settles [5]

extension of the inviscid shock wave upstream until their common intersection point. By basing the conical coordinate system about this location, the collapse of the flow features along arcs centered about this origin is achieved. It should be noted, as is argued by Rodi and Dolling [8], that this symmetry is not conical in the strictly mathematical sense. Pure conical symmetry requires a decay in gradient-dependent quantities as r , distance from the coordinate origin, decreases whereas, in the current case, they remain constant. Nonetheless, this terminology is used throughout the literature and in the present work.

It is also important to recall that this quasi-conical symmetry is only present in the downstream or farfield region. Nearer the leading edge is the inception region; in this region, the SWBLI is still developing and quasi-conical symmetry is not yet observed [15, 16]. The length of the inception region is a quantity of interest as its termination marks the beginning of the symmetric region. However, this is also a difficult variable to quantify since this process occurs asymptotically and the length of this region also varies with the strength of the interaction from negligibly short to longer than the length scale of a given test article [14]. The locations of the VCO, inception region, and farfield region for a given test case are visualized in the sketch from Lu et al. [6] provided in Fig. 1.6.

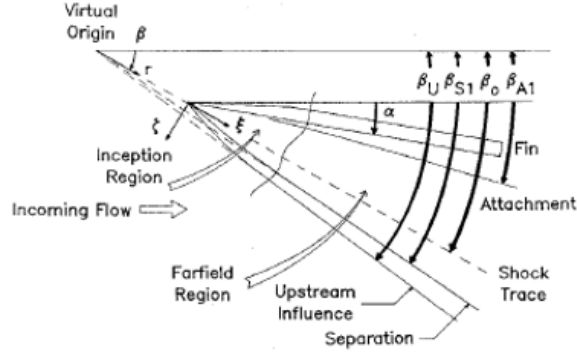


Figure 1.6: Characteristic flow features of the SWBLI including the virtual conical origin, inception region, and farfield region. From Lu et al. [6].

Other than these canonical flow features, another significant part of the fin-induced SWBLI problem is the pressure and heat-flux distributions that are generated on the plate surface. In fact, these values may be more relevant than the flow structures when considering their effects in terms of high-speed vehicle design. Over the years, numerous studies [5, 7, 8, 16–24] have investigated the spanwise or azimuthal pressure distribution generated by this SWBLI and, from these studies, several characteristic features of the pressure distribution have been identified. These features are shown in the sketches of the typical distribution provided by Holden [7] and Rodi [8]. From these sketches, it can be seen that the pressure shows a slow rise from the freestream starting at the line of upstream influence. Further inboard, near the shock-wave location, the pressure maintains a relatively constant value at what is typically referred to as the pressure plateau region. This plateau region can also exhibit a local peak and trough, as is shown in Fig. 1.7b. Moving closer to the fin, the pressure experiences a rapid increase as it reaches its peak near the location of primary reattachment.

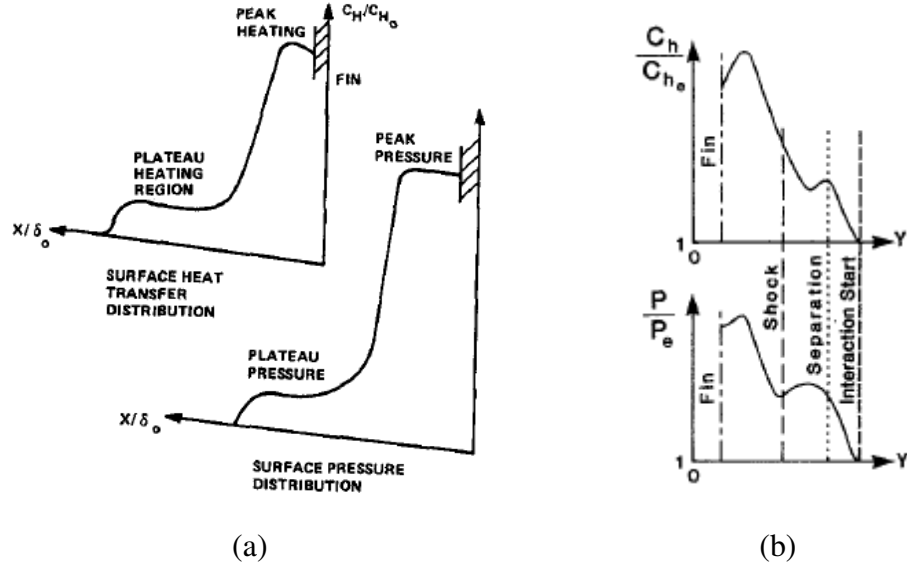


Figure 1.7: Typical heat-flux and pressure distributions from (a) Holden [7] and (b) Rodi [8].

Despite there being substantially less historical data available which includes the heat-flux distribution generated by this SWBLI, there are nonetheless certain features that have appeared consistently across the extant literature [7, 8, 23, 25–27]. Like the pressure distribution, there is a gradual rise from the unaffected freestream followed by a plateau or peak and trough near the inviscid shock-wave location. Once again, further inboard, near the location of primary reattachment, the maximum heat-flux of the distribution is reached.

From these studies, it can be seen that this fin-induced SWBLI results in a complex flowfield which varies drastically as one moves throughout the parameter space. This does not even include many of the more specific studies that may focus on other quantities of interest such as pressure fluctuations, unsteadiness, or surface features on the fin. With such a large number of relevant parameters and the wide variation of the physics throughout the parameter space, many open research questions remain about this SWBLI. This motivates the current work.

1.4 Open research questions and scope of current work

From the aforementioned studies, it is clear that a substantial research effort has gone into characterizing the fin-induced SWBLI. Both experimental and computational investigations have been conducted over the years; however, they have been restricted almost exclusively to cases where the boundary layer is either fully laminar [17, 28] or, more commonly, fully turbulent [3, 5–8, 12, 14, 18–27, 29–44]. Most studies have focused on supersonic as opposed to hypersonic flows. Specifically, of those cited above, the majority are focused on supersonic Mach numbers between 2–4 [3, 5, 6, 12, 14, 17, 18, 20–22, 25–36], with only a limited number in the hypersonic regime at Mach numbers of 5 [8, 19, 24, 37–42], 6 [23], 8.2 [43, 44], and 11 [7]. Additionally, there are a number of parameters that can be varied in these experiments: fin sharpness, deflection angle, and sweep are all variable along with the usual flow properties of Mach number, Reynolds number, incoming boundary-layer state, et cetera. This has resulted in many campaigns including the sharp-fin-induced SWBLI as part of a broader survey of SWBLIs as opposed to a detailed investigation of its specific geometry, which, in term, has left several specific, yet important, behaviors without a comprehensive description.

Two of the foremost among these behaviors are the surface heat flux generated by the SWBLI and the unsteadiness of the interaction [1, 45]. Despite the studies that have been conducted focusing on these behaviors, such as that by Rodi [8] referenced in Fig. 1.7 where heat flux is analyzed or those by Schmisser [24, 41] and Gibson et al.[38] examining unsteady wall pressure fluctuations, there is by no means a comprehensive understanding of these phenomena. With this in mind, it is clear that the area of transitional hypersonic flows poses a situation of particular importance since transition at high Mach numbers is known to be associated with high levels of both heating and unsteadiness. Although, intuitively, one may expect the behavior of a transitional hypersonic flow to fall between that

of laminar and turbulent flows, this is not the case. For example, Sandham et al. [46] concluded that, for the case of an externally-generated shock wave impinging upon a flat plate (Fig. 1.1a), the highest levels of wall heat transfer occurred when the flat-plate boundary layer was transitional, not fully turbulent. Similarly, experiments by Murphree et al. [47] showed that the separated flow region generated by the SWBLI of a cylinder mounted on a flat plate (similar to Fig. 1.1e) exhibited larger variations in both scale and shape for a transitional incoming boundary layer compared to a turbulent one. Experimental studies on flared cones have shown that high-frequency second-mode disturbances, known to be the dominant instability for axisymmetric bodies [48], can be significantly modified by a SWBLI [49]. These disturbances can display nonlinear behavior as they develop in a transitional boundary layer [50] and have significant implications on hypersonic vehicle design. With these examples in mind, it is clear that transitional hypersonic SWBLIs have an important influence on the flow properties for a variety of geometries and deserve further examination.

Although there is a particular need to focus on the transitional case, there are also notable gaps in the understanding of the surface heat transfer for the turbulent case [45]. As mentioned, several investigations have been made into the heat-flux distribution of this SWBLI; however, many of them were done a relatively low spatial distribution. More significantly, virtually none of these studies focusing on heat transfer have any description of how this surface heating varies with time. For an interaction that may exhibit significant unsteadiness, a temporal description of the heat flux, a possible design-limiting parameter, is essential.

A more easily overlooked but nonetheless important feature of this flowfield that has not been studied in great detail is the evolution of the boundary layer and other flow structures as they are processed through the SWBLI. Of the studies that have been conducted using optical diagnostics, many rightly take advantage of a fin-align optical axis to utilize

the quasi-conical symmetry of the interaction. This results in a clear pictures of the flow features in the $\xi_n - y$ plane of Fig. 1.3, yet it does not provide any information of how the flowfield develops in a streamwise direction. This is a critical shortcoming when considering this problem in relation to boundary-layer transition over the entirety of the vehicle.

Finally, a particularly difficult aspect of this SWBLI is the behavior at low fin angles. This is a challenging problem to approach experimentally because, with fin-aligned optical diagnostics, the facility would need an immense streamwise spacing between test-section windows to be able to investigate such angles. However, when considering these geometries as analogues to control surfaces on hypersonic vehicles, these small fin angles are exactly the ones that would be encountered when implemented in these situations. Many of the larger angles considered are not realistic for control surface deflection angles.

With these open questions in mind, it is the goal of this study to investigate both the surface heat flux and streamwise development of the flowfield for the transitional and turbulent sharp-fin-induced SWBLI. This investigation is done through a series of experimental campaigns in the University of Maryland's HyperTERP and high-temperature Ludwig tube (HTLT) facilities. Both of these campaigns make use of fast-response high-sensitivity temperature-sensitive paint (TSP) for heat-flux measurements and a novel implementation of high-speed schlieren imaging, with the optical axis passing through the test article via flush-mounted windows, as an optical diagnostic.

The transitional case is investigated first with an experimental campaign conducted in the HyperTERP facility. This campaign also functioned as a validation for the plan-view high-speed schlieren and the TSP methodology, which had not been previously implemented in a facility of this scale. The results of the transitional campaign are discussed in Ch. 4. Since the HTLT facility was only recently commissioned, a characterization of the freestream flow was necessary before any further scientific investigations could be made. Chapter 3 discusses this characterization process and its results. Subsequently, a second

experimental campaign was conducted in the HTLT facility to investigate the fin-induced SWBLI with a turbulent incoming boundary layer. Due to the greater range of capabilities of this facility as well as the lessons learned during the transitional campaign, a more comprehensive and detailed study of the turbulent case was able to be conducted. The results of this campaign are presented in Ch. 5. Lastly, Ch. 6 summarizes the key findings of these investigations and discusses their contributions in the broader context of the ever-evolving understanding of these complex interaction and their implications for hypersonic vehicle design.

Chapter 2: Experimental Methodology

2.1 Facilities

2.1.1 HyperTERP reflected-shock tunnel

All experiments focusing on the transitional fin-induced SWBLI were conducted in the University of Maryland's HyperTERP reflected-shock tunnel. A schematic view of this facility is presented in Fig. 2.1. The test section of the HyperTERP facility is of the free-jet type, with an internal diameter of 30.5cm and a nozzle exit diameter of 22cm. The test section is equipped with four 15.2cm windows, mounted at 90-degree intervals, for optical access. This tunnel was operated using nitrogen as the test gas and a mixture of nitrogen and helium as the driver gas; to maximize the available test time, the tunnel was run under (approximately) tailored conditions, which, together with the desired flow enthalpy, dictated the nitrogen/helium ratio in the driver gas and the pressure ratio of the driver/driven gases [51].

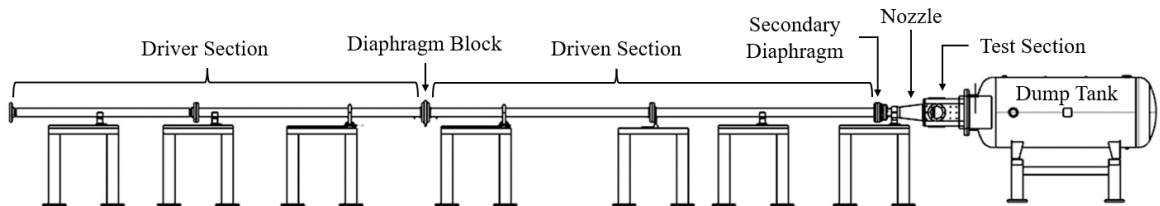


Figure 2.1: Schematic of the HyperTERP reflected-shock tunnel

Condition	p_0 [MPa]	T_0 [K]	$Re_m \cdot 10^6$ [1/m]	M_∞	U_∞ [m/s]	p_∞ [kPa]	T_∞ [K]	ρ_∞ [kg/m ³]	δ_ℓ [mm]
A	1.81	614	10.0	6.15	1065	0.98	72	0.0458	2.33
B	1.82	572	11.3	6.15	1027	0.99	67	0.0496	2.19
C	2.13	571	13.3	6.15	1026	1.16	67	0.0582	2.02

Table 2.1: HyperTERP test conditions.

Three test conditions were employed for the transitional SWBLI investigation, each of which was found to result in a transitional boundary layer (of varying maturity) within the region of interest on the flat-plate test article. The flow parameters for these conditions are provided in Table 2.1. The reservoir pressure was measured directly and the reservoir temperature was determined from the measured pressure and incident shock speed, by assuming an isentropic transition from the post-reflected-shock conditions. The steady test time was typically 7 – 8 ms and was determined based on the reservoir pressure trace gathered during each test. An example of a typical reservoir trace with the steady test time indicated can be seen in Fig. 2.2. All results presented in the transitional case analysis (Ch. 4) are taken from the steady-flow time unless otherwise indicated. From Pitot-probe measurements, the freestream Mach number was determined to be 6.15 ± 0.06 , where the standard deviation is determined from the square root of the mean variance throughout the steady test time of the centerline probe at conditions A and C. The freestream conditions provided in Table 2.1 were calculated assuming a perfect-gas, isentropic expansion to the freestream Mach number. The laminar boundary-layer thickness at the leading edge of the fin, δ_ℓ , was calculated assuming a compressible, self-similar boundary layer according to the method described by Anderson [52]. Note that the values presented in Table 2.1 are nominal values and vary slightly between each run. Over the steady test time, the reservoir-pressure unsteadiness is around 2% (standard deviation), variation in the mean pressure between shots is roughly 1.3%, and the measurement has a systematic uncertainty of approximately 1.6%;

the accuracy of the shock-speed is estimated to be within ± 5 m/s, resulting in a 0.4% uncertainty in the reservoir temperature. The exit Mach number deviates from the centerline value by no more than 1% within 76 mm of the centerline [49].

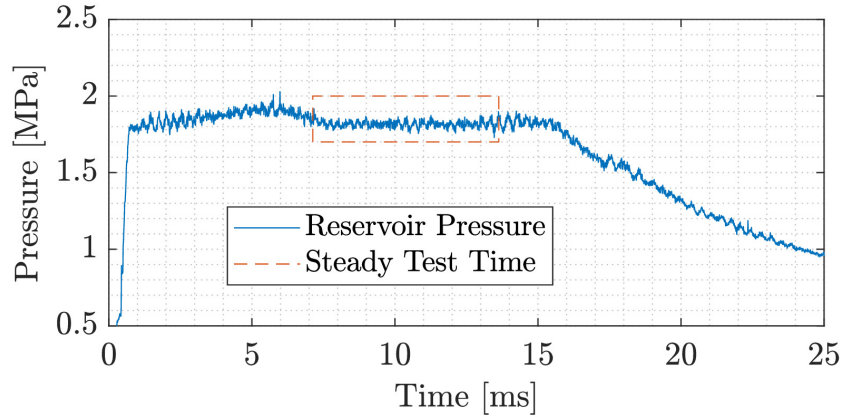


Figure 2.2: Reservoir pressure trace for condition A with the steady test time boxed.

2.1.2 High-temperature Ludwieg tube facility

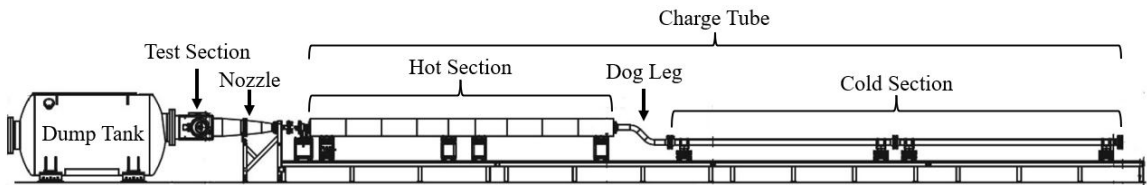
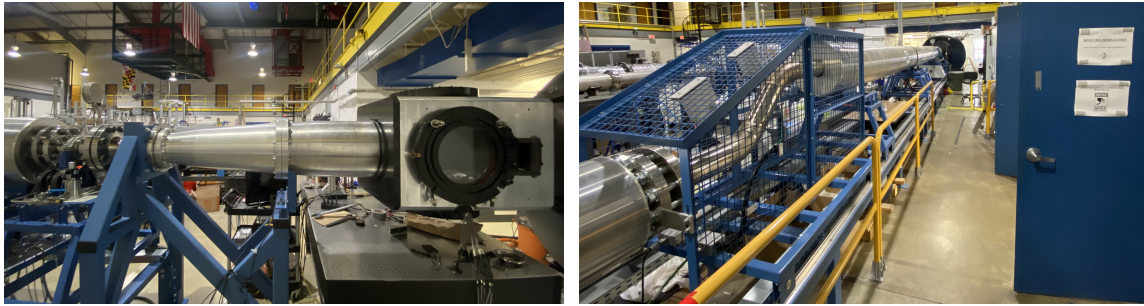


Figure 2.3: Schematic of the high-temperature Ludwieg tube facility.

All experiments focusing on the case of the turbulent fin-induced SWBLI were conducted in the University of Maryland's recently commissioned high-temperature Ludwieg tube (HTLT) facility. The freestream flow characterization of this facility was a significant portion of the present work; therefore, a detailed description of the facility's construction and operating principles is given below. The characterization process is discussed in detail in Ch. 3.

The HTLT facility is composed of four main sections, namely the charge tube, the converging-diverging nozzle, the test section and a large vacuum (dump) tank, as shown in Fig. 2.3. The charge tube of the tunnel is made up of an 8 m-long, 121 mm-diameter hot section, a 12 m-long, 139 mm-diameter cold (but still heated) section, and a dog-leg transition which is 1.7 m long with a vertical offset of 0.405 m and a diameter of 119.7 mm. The vertical displacement provided by the dog leg allows the gas in the two sections to be held at two separate temperatures without thermal stratification. Since only a portion of the gas within the hot section of the charge tube will be used for a given test, the gas within the cold section of the charge tube can be kept at a lower temperature without affecting the freestream flow conditions. This allowed the cold section of the charge tube to be constructed from more economical stainless steel than the Inconel alloy needed for the hot section without sacrificing overall performance. There are two interchangeable nozzles for the tunnel: a Mach-6.25 nozzle which is 1.97 m long with an exit diameter of 35.7 cm and a Mach-8 nozzle which is 2.34 m long with an exit diameter of 45.0 cm. The test section is of the free-jet type with an internal diameter of 60 cm. The test section has four 32-cm diameter windows mounted at 90-degree intervals for optical access, with four additional feedthrough locations allowing for instrumentation of test articles. The entirety of the tunnel exhausts into a dump tank that is approximately 14.5 m³ in volume. Photographs of the facility can be seen in Fig. 2.4.



(a)

(b)

Figure 2.4: High-temperature Ludwig tube facility (a) piston housing, nozzle, test section, and (b) dog leg.

The tunnel flow is initiated through the use of a fast-acting piston system which is depicted in Fig. 2.5. The system is composed of a free-floating copper piston, a piston housing mounted inside the hot section of the charge tube, and a series of fast-acting valves. The piston housing isolates a small volume of gas behind the piston body from the rest of the charge tube, making one side of the piston (front) exposed to the charge tube pressure and one side (back) exposed to this isolated volume. This small volume is connected via piping to the charge tube and an atmospheric exhaust vent; each of these lines contains a fast-acting valve.

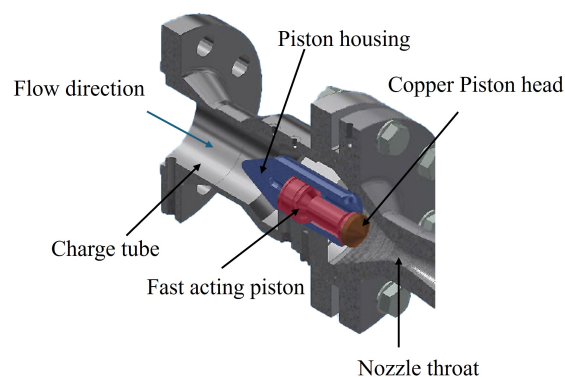


Figure 2.5: Piston block.

Before a test, the valve to the charge tube is kept open, ensuring the pressure on the front and rear faces of the piston are exposed to the same pressure. To begin a test, the valve connecting the volume within the piston housing to the charge tube is actuated, isolating the piston chamber from the charge tube. Next, the valve connecting the piston housing to the atmospheric exhaust vent is actuated, allowing the volume behind the piston to be reduced to ambient pressure. This generates a pressure difference across the piston which retracts the piston head from the nozzle throat and allows the main tunnel flow to begin. After the steady test time has ended, this process is conducted in the reverse order and causes the piston to move forward, sealing it against the nozzle throat and concluding the test. This entire sequence is typically concluded in less than 200 ms.

The facility is able to operate at charge tube pressures from 10-60 bar and charge tube temperatures ranging from approximately 500-850 K (hot-section temperature). The lower limit of the pressure range is set by the requirement of a sufficient pressure gradient to move the fast-acting piston and allow the tunnel to start. The low temperature limit of 500 K is determined by temperature ratio between the hot and cold sections of the charge tube which is given as:

$$T_{cold} = T_{hot} \left(\frac{d_h}{d_c} \right)^4 = 0.5742 \cdot T_{hot} \quad (2.1)$$

where d_h and d_c are the diameters of the hot and cold section of the charge tube, respectively [53]. This ratio is used to minimize the reflection of the expansion wave which propagates through the charge tube at tunnel startup. With this relation in mind, a hot-section temperature of 500 K requires a cold-section temperature of 287 K or 14 °C which is roughly the ambient temperature of the laboratory which houses the tunnel. Since there is no active cooling on the cold section, this marks the lower limit of the facility's operating

temperature range. The upper limits on both pressure and temperature are set by the safe operating limits of the materials used to construct the facility. Several cases at which the facility is able to operate near these limits are outlined in Table 2.2.

Mach Number	p_{Tube} [bar]	T_{Tube} [K]	p_0 [kPa]	T_0 [K]	$Re_m \cdot 10^6$ [1/m]
6.25	10	500	911	487	7.28
6.25	10	850	913	830	3.10
6.25	60	500	5465	487	43.7
6.25	60	850	5477	830	18.6
8	10	730	954	721	2.23
8	10	850	954	840	1.73
8	60	730	5727	721	13.4
8	60	850	5729	840	10.4

Table 2.2: Example tunnel operating conditions.

To see the effects of deviating from the temperature ratio prescribed by Eq. 2.1, a series of tests were conducted at Mach 6.25 with various offsets for T_{cold} . For each test, $p_{Tube} = 30$ bar and $T_{hot} = 565$ K were held constant, while T_{cold} was offset in increments of 10 K; the resulting Pitot rake traces are plotted in Fig. 2.6. From these results, it can be seen that variations away from the theoretically prescribed value of T_{cold} result in only small changes to the Pitot rake traces. Any slight differences in flow steadiness or steady test time seen in Fig. 2.6 could also be caused by anticipated shot-to-shot variations of the facility. Therefore, all subsequent runs were conducted using the theoretical value of T_{cold} as given by Eq. 2.1. Additionally, tests with offsets in T_{cold} are included among the calibration data presented in Ch. 3.

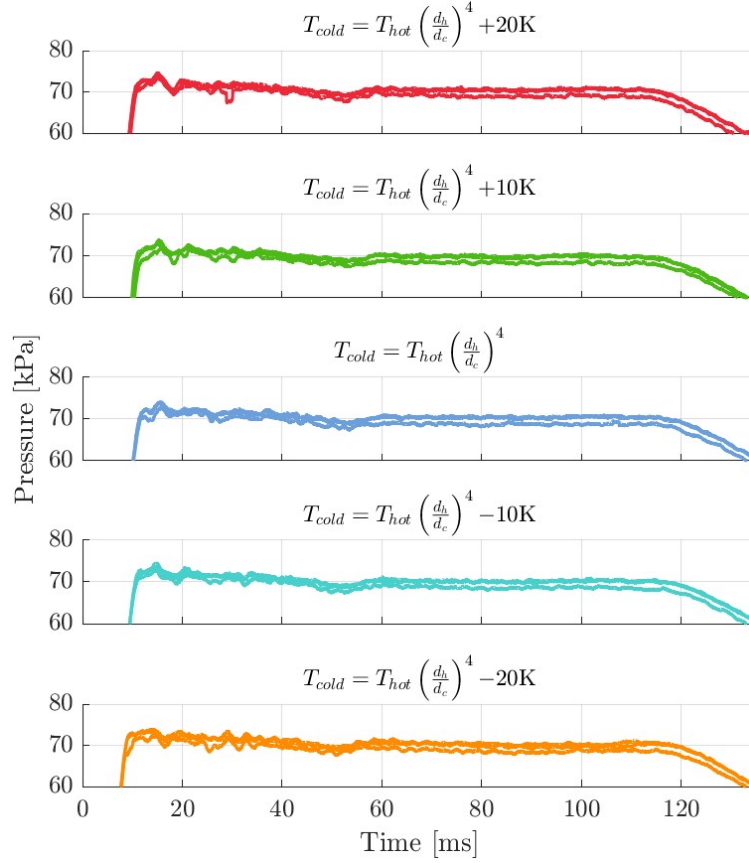


Figure 2.6: Pitot rake traces at different offsets of T_{cold} .

Condition	p_{Tube} [bar]	T_{Tube} [K]	p_0 [MPa]	T_0 [K]	$Re_m \cdot 10^6$ [1/m]	M_∞	U_∞ [m/s]	p_∞ [kPa]	T_∞ [K]	ρ_∞ [kg/m ³]	δ_t [mm]
A	20	550	1.82	536	12.4	6.25	977	0.897	61	0.0514	2.69
B	30	550	2.73	536	18.6	6.25	977	1.35	61	0.0771	2.20
C	40	550	3.64	536	24.9	6.25	977	1.79	61	0.1027	1.90
D	50	550	4.56	536	31.1	6.25	977	2.24	61	0.1284	1.70

Table 2.3: HTLT campaign test matrix.

Four test conditions were used in the investigation of the turbulent fin-induced SWBLI and are presented in Table 2.3. Through the use of high-speed spanwise schlieren (similar to that described in §2.2.2), it was verified that each of these test conditions resulted in a turbulent incoming boundary layer at the region of interest. This boundary-layer development and transition to turbulence is shown from the leading edge of the test article in Fig. 2.7a,

where transition begins near $x = 175$ mm; Fig. 2.7b shows a fully turbulent boundary as it enters the region of interest at $x = 350$ mm.

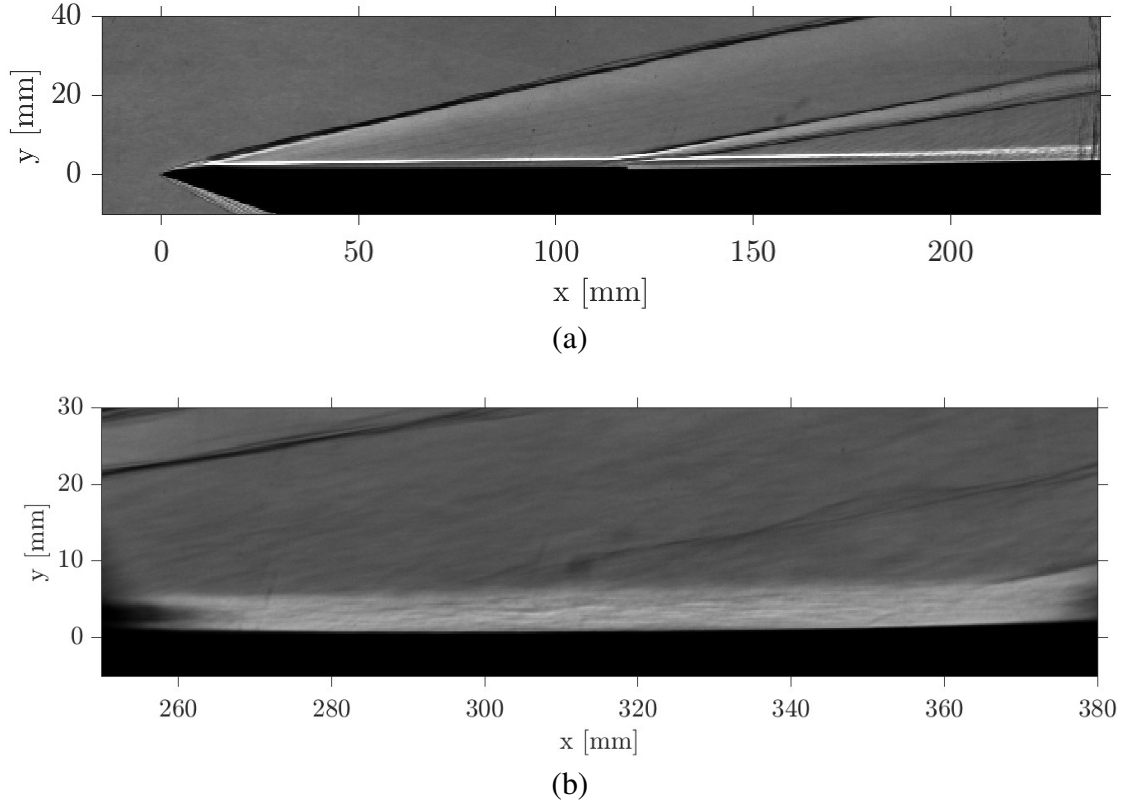


Figure 2.7: Spanwise schlieren showing (a) the leading edge of plate with a turbulent boundary layer at $x \approx 200$ mm and (b) a fully turbulent boundary layer in the region of interest. Note: region of interest starts at $x = 350$ mm.

For each of these test conditions, the reservoir pressure and temperature were measured directly. Because of the high temperatures encountered within the charge tube, a calorically imperfect gas model is implemented when calculating the stagnation conditions according to

$$\gamma = 1 + \frac{\gamma_p - 1}{1 + (\gamma_p + 1) \left[\left(\frac{\theta_v}{T} \right)^2 \frac{e^{\theta_v/T}}{(e^{\theta_v/T} - 1)^2} \right]} \quad (2.2)$$

where γ_p is the heat capacity ratio under perfect gas assumptions, θ_v is the characteristic vibrational temperature, and T is the temperature of the charge tube. To obtain the freestream conditions given in Table 2.3, an isentropic expansion from the charge tube reservoir through the nozzle is assumed. The laminar boundary-layer thickness at the fin leading edge is again given for reference and was calculated in the same manner as that in Table 2.1. With these test conditions, the typical steady test time was roughly 100 ms. Analysis of the spanwise schlieren showed that the time frame from approximately 40 – 70 ms after flow arrival contained the steadiest flow; therefore, this time frame is considered the steady test time and all data presented in the turbulent case analysis (Ch. 5) will be from this period unless otherwise noted. These are again nominal operating conditions and vary slightly from shot to shot. Further details on the flow environment are provided with discussion of the freestream characterization process in Ch. 3.

2.1.3 Test articles

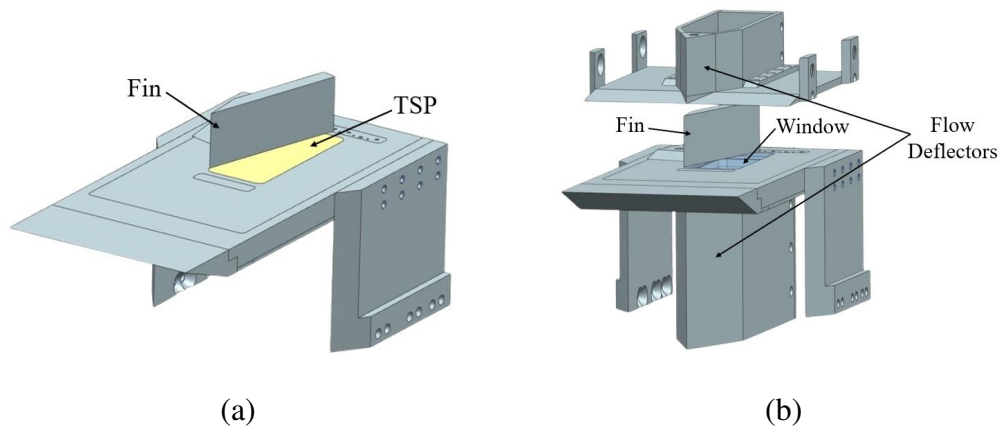


Figure 2.8: Test articles used in the HyperTERP campaign configured for (a) temperature-sensitive paint and (b) schlieren.

The test article used throughout the transitional campaign in HyperTERP was a modular flat-plate/fin model. This model consisted of a flat, hollow steel plate that measured

160 mm wide by 350 mm long by 22.2 mm thick, with a nominally sharp leading edge and a lower incidence angle of 20° . In the center of the plate, cutouts allowed for the placement of inserts for various diagnostic techniques: in this case, windows for optical techniques (i.e., schlieren) or engineering thermoplastics for temperature-sensitive-paint (TSP) measurements. The steel fin measured 44.5 mm tall, 127 mm long, and had a sharp leading edge with a 20-degree angle on the leeward side. The fin was secured to the main plate via an adjustable base, which allowed the deflection angle of the fin to be varied continuously from 0° to 15° ; rotation was about the fin's leading edge, which remained at 198 mm downstream of the plate leading edge and offset 25.4 mm from the model centerline. For the transitional SWBLI tests, deflection angles of 5° , 10° , and 15° were investigated as well as a case with no fin attached. The center cutout region of the plate was roughly rectangular with a streamwise length of 120.7 mm and a spanwise width of 50.8 mm. The entire assembly was mounted into the HyperTERP test section on sharp-leading-edged legs which attached to the sides of the flat plate and were positioned so as not to influence the flow in the region of interest. Mounting the model to the side of the tunnel (i.e., so that the flat plate was vertical) facilitated the implementation of the schlieren imaging to be discussed shortly. A schematic of the model configured for temperature-sensitive paint experiments can be seen in Fig. 2.8a. For experiments where schlieren was employed, flow deflectors were installed both above and below the test article (on either side when mounted). These deflectors served the purpose of preventing the flow on the underside of the flat plate or the shear layers exiting the nozzle from corrupting the data being collected in the region of interest on the top surface of the plate (initial experiments without the upper deflector showed that the boundary-layer content in schlieren images was completely overwhelmed by the shear-layer disturbances). This latter setup can be seen in Fig. 2.8b. The short flow length of the upper deflector ensured that its boundary layer remained laminar and had a negligible effect on the acquired data.

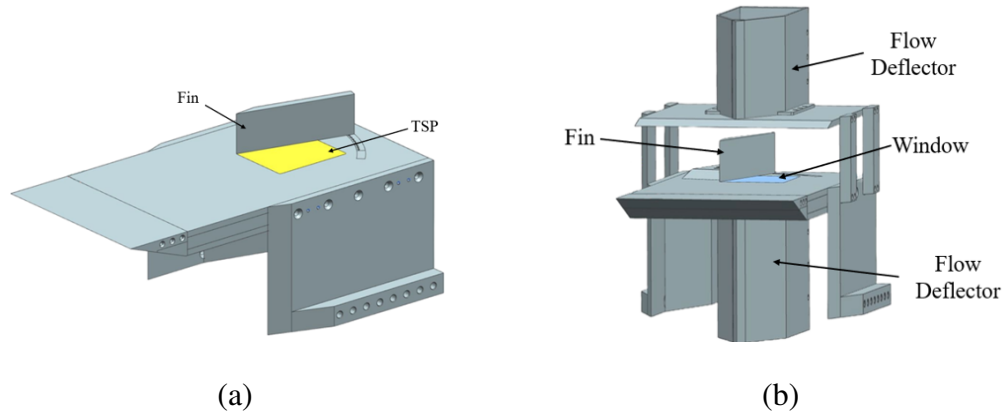


Figure 2.9: Test articles used in the HTLT campaign configured for (a) temperature-sensitive paint and (b) schlieren.

Likewise, a similar flat-plate/fin test article was fabricated for use in the HTLT facility. The HTLT model measured 279.4 mm wide by 565 mm long by 38.1 mm thick with a nominally sharp leading edge and a lower incidence angle of 20° . The fin was 63.5 mm tall by 190.5 mm long with a 20-degree leading-edge angle on the leeward side of the fin. The leading edge of the fin was maintained at a distance of 355.6 mm downstream of the plate leading edge. As in the HyperTERP model, the fin was able to be rotated about its leading edge continuously from 0° to 15° . For the turbulent SWBLI tests, fin angles of 2.5° , 5° , 7.5° , 10° , 12.5° , and 15° were investigated as well as the case with no fin attached. The center cutout region had a streamwise length of 127 mm and a spanwise width of 101.6 mm. Inserts made of thermoplastic were installed for TSP measurements, whereas windows were used for schlieren measurements. The test article was mounted into the HTLT test section on sharp-leading-edged legs with a vertical orientation to facilitate the implementation of diagnostics. As with the HyperTERP test article, a pair of flow deflectors were installed both above and below the main test article in an effort to isolate the flow directly over the plate. The upper flow deflector plate was situated 96.8 mm above the main plate surface (33.3 mm above the top of the fin). When assembled, the deflectors measured

500 mm from the top of the upper deflector to the bottom of the lower deflector, ensuring that any shear flows that develop on the surfaces of the 35.7 cm Mach-6.25 nozzle would be directed away from the region of interest. Renderings of the HTLT test article for each configuration can be seen in Fig. 2.9.

2.2 Diagnostics

2.2.1 Fast-response temperature-sensitive paint

Time-resolved TSP measurements were gathered in both the transitional and turbulent campaigns. To implement this technique the cutout region in the center of the flat plate was fitted with a thermoplastic insert. For the transitional campaign, both Ketron PEEK 1000 and Delrin acetal homopolymer were used. These materials were chosen for their density, thermal conductivity, and specific heat capacity, the values of which are listed in Table 2.4 (note that the reported physical and thermal properties of these materials vary among manufacturers; therefore, the values presented should be taken as nominal ones). Temporarily assuming the paint layer has a negligible effect on the heat-conduction process, the surface heat-transfer rate is given by Schultz and Jones [54]:

$$q(t) = \sqrt{\frac{\rho c k}{\pi}} \int_0^t \frac{dT/d\tau}{\sqrt{t-\tau}} d\tau \quad (2.3)$$

Similarly, the temperature rise on the surface is given by:

$$T = \frac{1}{\sqrt{\pi \rho c k}} \int_0^t \frac{q(\tau)}{t-\tau} d\tau \quad (2.4)$$

Therefore, the square root of the product of these values, that is $\sqrt{\rho ck}$, determines the extent of the temperature rise on the surface of the model, which, in turn, determines the resolution of the desired heat-flux measurements. Since the temperature rise on the surface (i.e. in the paint) should be maximized, $\sqrt{\rho ck}$ for the base material should be minimized to avoid heat conducting out of the paint layer and into the base material. PEEK was found to give superior results, but, since not all configurations in the transitional campaign test matrix were tested with PEEK and several runs were contaminated by diaphragm fragments passing through the field of view, Delrin results are also provided in the discussion presented in Ch. 4. For the subsequent turbulent campaign, PEEK is exclusively used for TSP measurements.

Material	ρ , Density [kg/m ³]	k , Thermal Conductivity [W/m K]	c , Specific Heat [J/kg K]	$\sqrt{\rho ck}$ [J/m ² K s ^{1/2}]
Delrin	1410	0.360	1465	743634
PEEK	1310	0.252	1240	409349
P-70 Polymer	1132	0.1968	2070	461150

Table 2.4: Material properties.

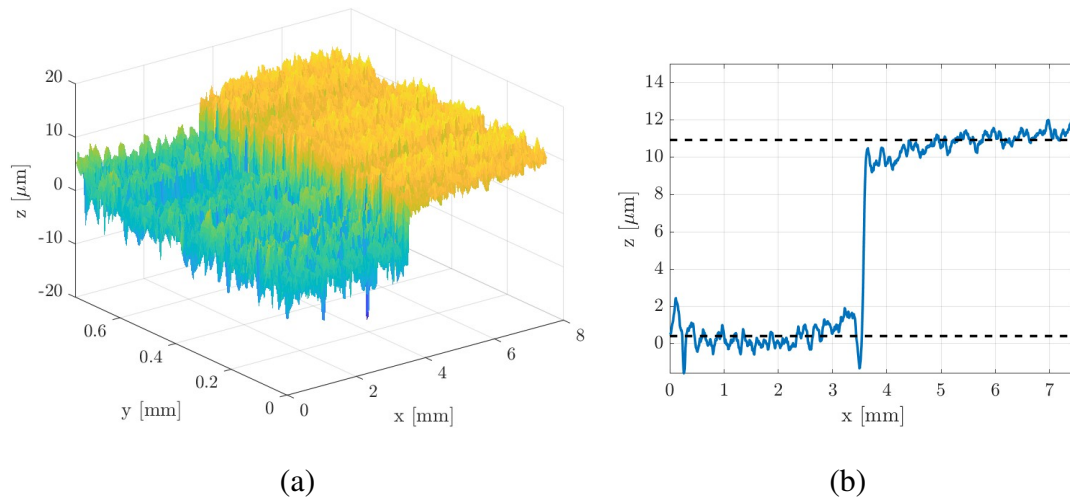


Figure 2.10: (a) Surface plot of paint thickness measurement and (b) mean surface profile.

Upon these inserts, a thin layer of high-sensitivity TSP was applied to the inset surface using an airbrush paint gun. This paint consisted of an ethanol base, a polyethylenimine P-70 binder, and a ruthenium tris(1,10-phenanthroline) dichloride (Ruphen) luminophore [9]. For the transitional test article, the thickness of the paint layer was estimated to be between $1.6 - 2.6 \mu\text{m}$ thick, as measured independently by a white-light interferometer and a profilometer. For the analyses presented in Ch. 4, a thickness of $2 \mu\text{m}$ was used and treated as a constant. For the turbulent case, a more precise measurement of the paint thickness was able to be made through the use of a Keyence interferometer. This interferometer measurement was able to provide a surface profile over a small region (roughly $8 \text{ mm} \times 0.75 \text{ mm}$) of the insert near the edge of the paint layer with an accuracy of $\pm 2.5 \mu\text{m}$; this surface profile is shown in Fig. 2.10a. The profile was averaged along the y -direction (Fig. 2.10b), and the mean distance of $10.5 \mu\text{m}$ between the painted and unpainted surfaces (dashed lines) was treated as a constant and used for the analyses in the turbulent case in Ch. 5.

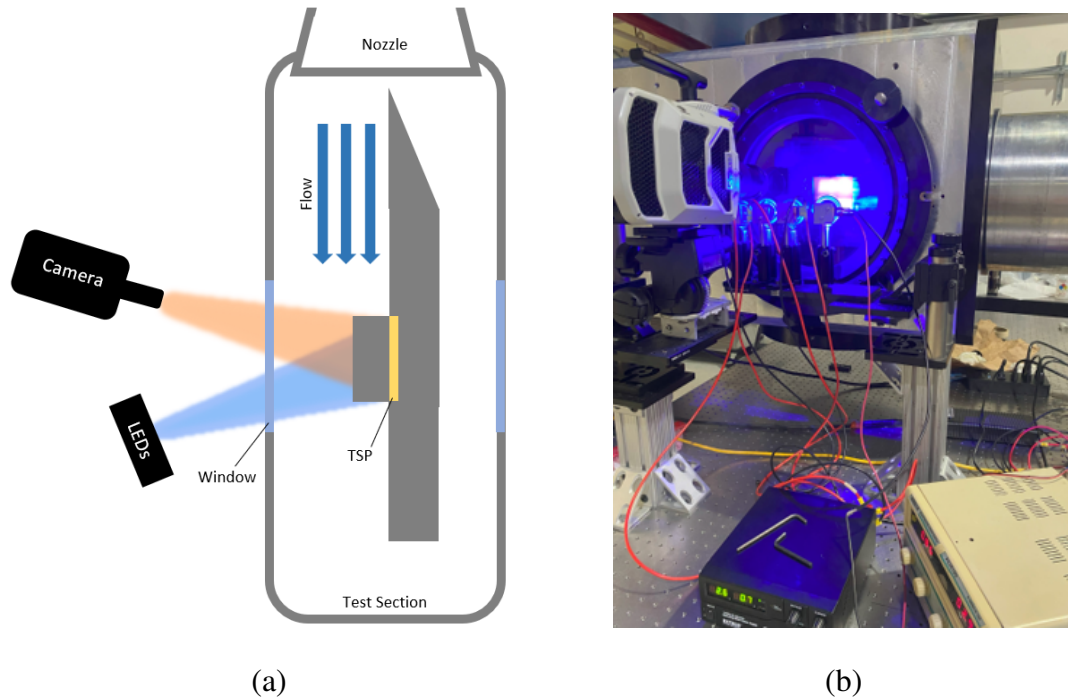


Figure 2.11: (a) Schematic of TSP setup and (b) photograph of TSP setup with illumination.

Once installed into the test section, the painted surface was illuminated using a set of blue ($\lambda = 460\text{nm}$) LEDs focused through a grouping of lenses. A Phantom v2512 camera was used to acquire the emitted light; a bandpass filter centered at 590nm with a full-width-half-max bandwidth of 60nm was placed in front to remove reflections and extraneous emissions. A schematic of the TSP setup and a photograph of the illuminated test article are shown in Fig. 2.11. This excitation and measurement method was determined based on the absorption and emission spectra of the Ruphen luminophore, shown in Fig. 2.12.

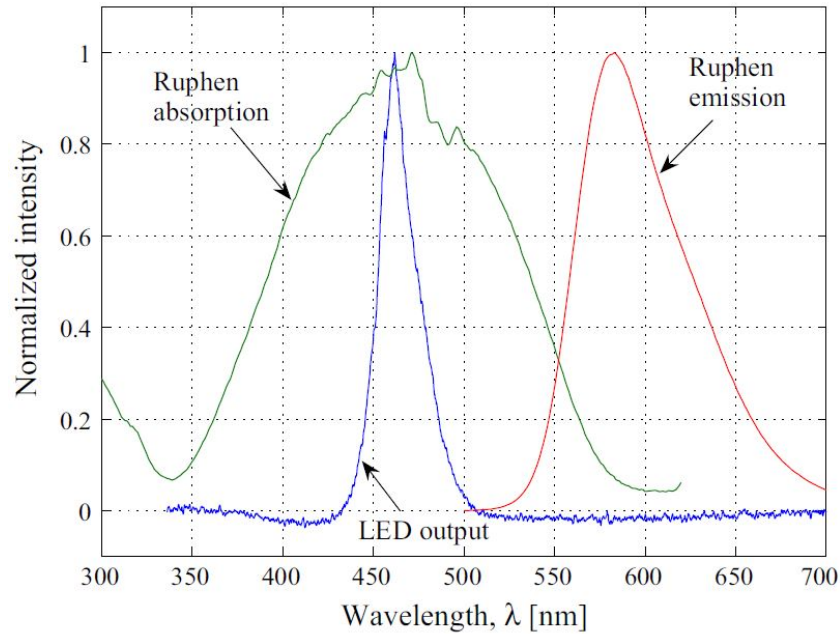


Figure 2.12: Absorption and emission spectra of the Ruphen luminophore overlaid with the output of the blue LED light source. From Ozawa [9].

The typical camera frame rate for the transitional campaign ranged from 25,000 – 30,000 frames per second, with corresponding exposure times of $39.5 - 32.9\mu\text{s}$. The camera resolution was 512×208 with 4.11pix/mm for the 5° and 10° tests and 896×400 with 7.54pix/mm for the no-fin and 15° tests. For the turbulent campaign, the frame rate for all tests was 70,000 frames per second with a corresponding camera exposure time of $13.8\mu\text{s}$. The camera resolution was 640×480 with $3.76 - 4.19\text{pix/mm}$.

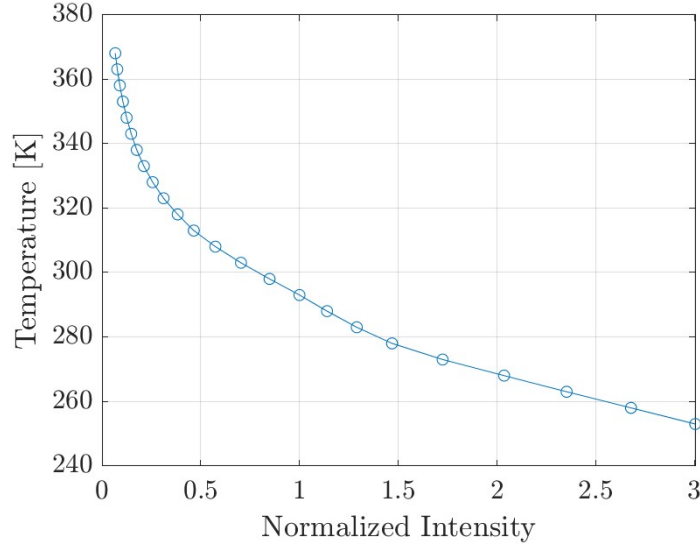


Figure 2.13: Paint calibration curve.

Once the raw TSP data were gathered during the tests, the time-resolved surface temperature distribution of the test article was determined using the calibration curve (Fig. 2.13) from Ozawa et al.[9]. The temperature change for the transitional case over the steady test time is shown for each configuration in Fig. 2.14. We see that the total temperature rise is around 1 K for the no-fin case and 3 K for the 15° case. These changes, occurring over a steady test time of 7 – 8 ms, motivates the need for the high-sensitivity TSP formulation employed here.

Heat fluxes were computed using the Green’s function approach described by Whalen [55]. This approach accurately models the influence of the finite thickness of the paint layer, which is less accurately treated by the alternative Liu et al. method [56] and neglected entirely in the method of Cook and Felderman [57]. While less important for mean measurements, accounting for the effect of this layer becomes more critical for the short time scales of interest here. Tikhonov regularization is implemented within the method to reduce noise in the derived instantaneous heat-flux distributions.

There are several sources of uncertainty that influence the heat-flux calculations. Ozawa

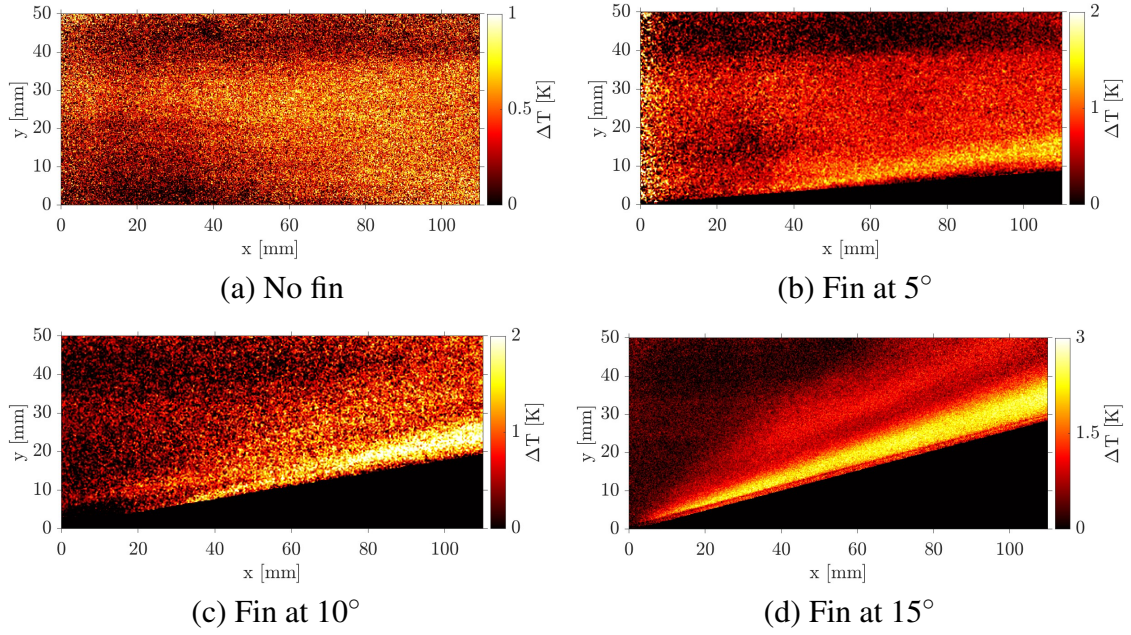


Figure 2.14: Surface temperature changes over the steady test time for the (Transitional, Condition A, Delrin).

et al. [9] found roughly 11% uncertainty due the temperature-intensity calibration, a 4.5% contribution to the uncertainty from the paint thickness, and a further 1% from temperature interpolation. Another contributor is the deviation of the thermal properties of the base layer from those given in Table 2.4. Although the supplier of these materials did not provide an estimation of these variations, they are assumed to be within $\pm 5\%$. Finally, an additional 1% will be assumed from the Green's function heat-flux reconstruction. This results in an overall experimental uncertainty of 13% which will be assumed for all heat-flux results shown; however, it will not be plotted as it is common to all experiments in both the transitional and turbulent campaigns.

2.2.2 High-speed schlieren

A standard Z-type schlieren with a vertical knife-edge, Phantom v2512 camera, and a Cavilux HF laser as the light source was used throughout the transitional campaign. The

two spherical mirrors used to collimate and refocus the light beam are 152 mm in diameter and have focal lengths of 1.52 m. The schlieren method employed an optical path through the surface of the flat plate, this being possible with windows installed flush with the upper and lower surfaces of the plate, as illustrated in Fig. 2.15. The camera frame rate for a given test ranged from 74,000 – 320,000 frames per second; the corresponding camera resolution was 768×400 with 6.94 pix/mm for the low frame rate tests and 768×80 with 6.45 pix/mm for the high frame rate tests. The pulse width of the laser in all cases was 20 ns. The camera was typically mounted horizontally, but in some cases (for which the higher frame rate was desired) rotated to match the fin angle and maximize the field of view at the reduced resolution.

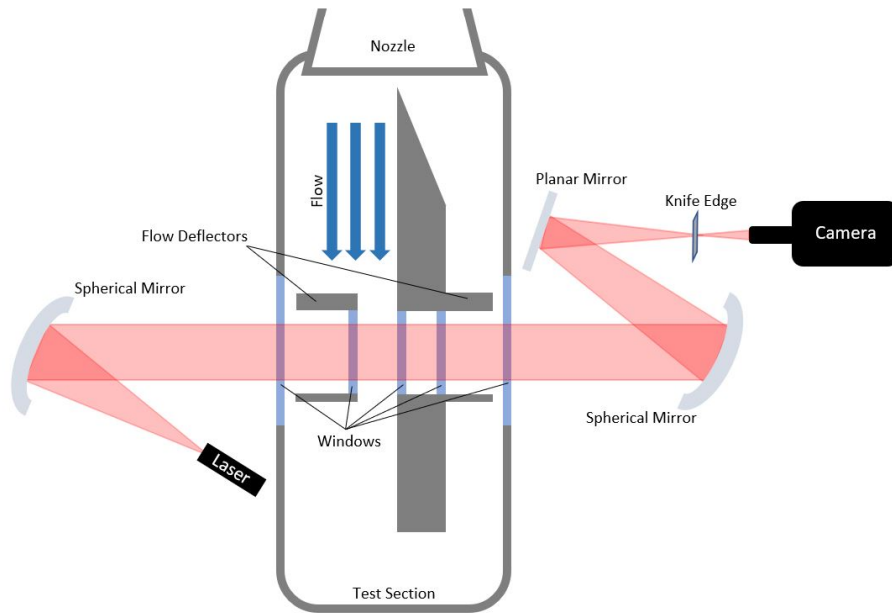


Figure 2.15: Schematic of the schlieren setup in the HyperTERP facility.

For the turbulent case, a similar schlieren setup was used with the substitutions of an LED as the light source and parabolic as opposed to spherical mirrors. The parabolic mirrors are 304.8 mm in diameter and have focal lengths of 2.54 m. Again, the optical axis passed through the upper and lower surfaces of the test article. For the no-fin case, a

frame rate of 380,000 frames per second with 256×128 and 1.88 pix/mm was used; for tests at angles of attack between $2.5^\circ - 12.5^\circ$ the frame rate was 320,000 frames per second with 384×128 and 1.98 – 2.87 pix/mm. To account for the larger spanwise extent of the interaction in the 15° case, the camera resolution was set to 256×144 ; all other properties were unchanged.

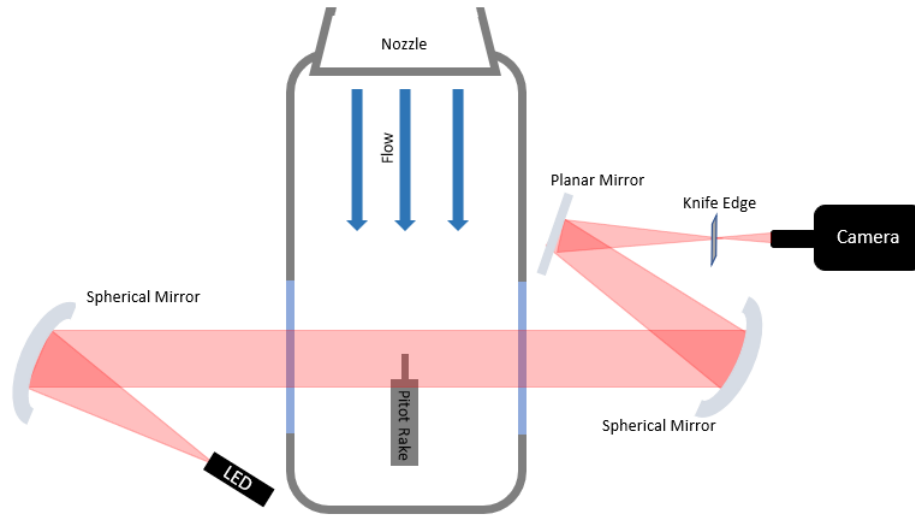


Figure 2.16: Schematic of the schlieren setup for HTLT characterization.

For the HTLT characterization, a Z-type schlieren with a horizontal-knife edge, Phantom v2640 camera, spherical mirrors, and a LED light source was used to visualize the flow structures passing over the center portion of the Pitot rake. A schematic of this setup is shown in Fig. 2.16. For these tests a camera frame rate of 5,800 frames per second was used with a camera resolution of 1408×1600 and 15 pix/mm. This visualization helped give confidence that the transducer measurements were not being corrupted by any possible shear flows generated by the nozzle or test-section walls and also enabled identification of the end of tunnel startup and the arrival of the unstart shock. A typical schlieren image is shown in Fig. 2.18b, and the sequence in Fig. 2.17 demonstrates how the unstart shock propagating upstream disrupts the steady flow in the test section.

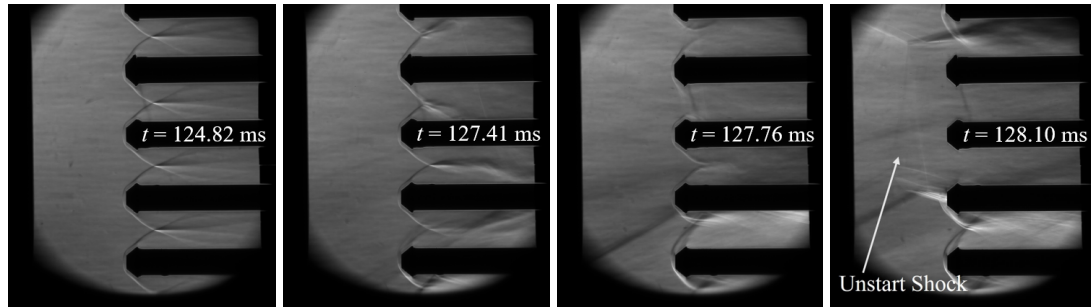


Figure 2.17: Schlieren images of tunnel unstart showing the propagation of the unstart shock upstream in the test section. Time from flow arrival shown.

2.2.3 Pitot rake measurements

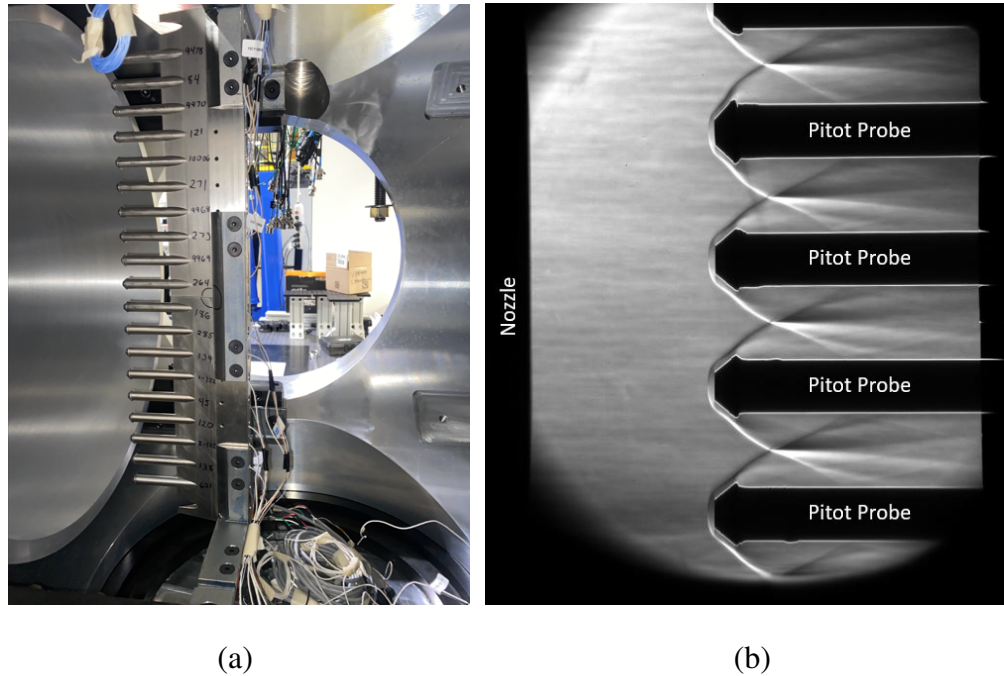


Figure 2.18: (a) Pitot rake instrumented in test section and (b) schlieren image of the Pitot rake 33 mm downstream of nozzle exit. Nozzle visible on left.

The Pitot rake used in the HTLT freestream characterization, shown in Fig. 2.18a, was instrumented with 14 Kulite XCQ-062 and 5 PCB Piezotronics pressure transducers. The center probe of the rake was aligned with the nozzle centerline and was instrumented

with a Kulite transducer; the lower half of the rake was instrumented entirely with Kulite transducers whereas the top half of the rake was instrumented with alternating Kulite and PCB transducers. The inter-sensor spacing was 23 mm. Tests were conducted with the vertically-oriented rake in an upstream position 33 mm from the nozzle exit and a downstream position 287 mm from the nozzle exit. All pressure measurements were recorded by a Dewetron DEWE2-M13 data-acquisition system at 2000 kHz. The data gathered from the two locations is qualitatively similar; therefore, results presented in Ch. 3 include Pitot measurements taken in both positions.

2.2.4 Femtosecond Laser Electronic Excitation Tagging

To supplement the measurements from the Pitot rake, femtomsecond laser electronic excitation tagging (FLEET) [58], a non-intrusive, molecular tagging velocimetry technique, was also used for the HTLT characterization. Molecular tagging velocimetry is used to measure the velocity of high-speed flows by "tagging" the gas molecules along the focal point of a laser beam. The tagged molecules are then tracked over a short span of time. A fast-gated intensified camera is used to capture an image of the "write" line, which is the initial position of the tagged molecules, then capture the "read" line, which is the tagged line's position after some delay (see Fig. 2.19). The velocity of the line, and hence the flow, can be computed using the distance between the "write" and "read" lines and the known time between captured images.

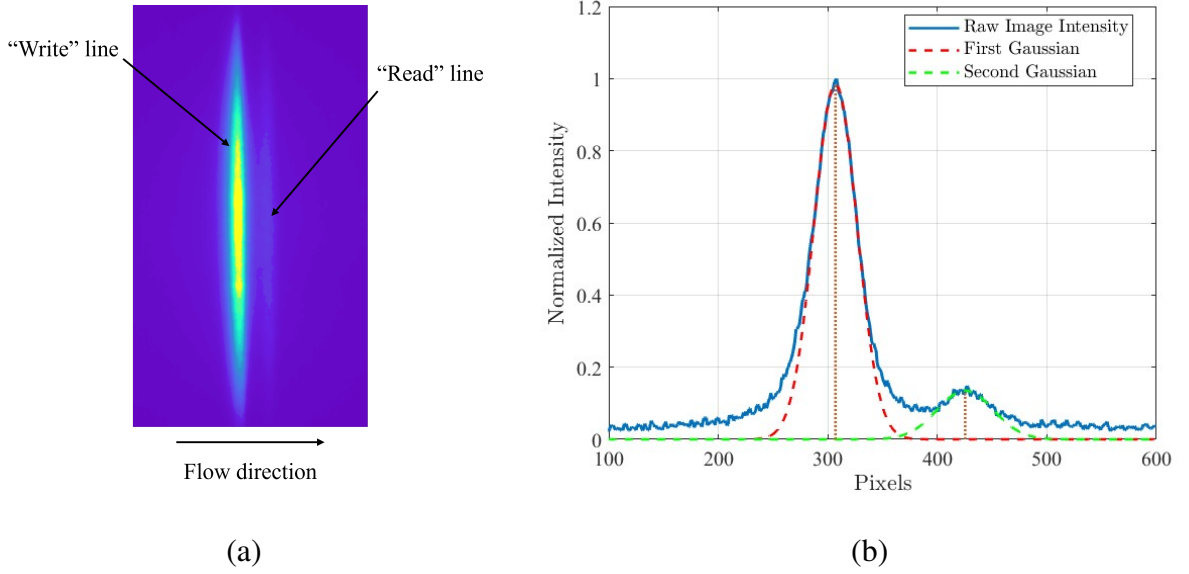


Figure 2.19: (a) FLEET lines captured at Mach 8 by the high-speed camera with a $2\mu\text{s}$ delay. (b) Gaussian curve fitting over normalized read and write line intensities.

FLEET uses a high-intensity, subpicosecond-duration laser pulse to generate atomic nitrogen, which produces a long-lived emission in the visible spectrum. For this study, a Spectra-Physics Mai Tai titanium-sapphire oscillator and a Coherent Hydra Ti:sapphire amplifier with pulsed chirp compression were used. This system outputs $\sim 7\text{ mJ}$ pulses centered at 810 nm with a 1 kHz repetition frequency. The laser is focused into the center of the test section with a cylindrical lens of 500 mm focal length. To gather images, a pco.dimax HD camera with a LaVision High Speed IRO intensifier was used. The intensity distribution across each pixel row of the FLEET images are averaged (every 20-30 pixels), then each intensity peak is fitted with a Gaussian distribution. The mean of each distribution then provides the approximate sub-pixel location of read and write lines (see Fig. 2.19b). Oxygen quenching of the nitrogen fluorescence in air is expected to decrease the FLEET signal by a factor of 10 [59]. For the purposes of this study, however, the oxygen quenching is low enough to produce a readable signal.

Chapter 3: High-temperature Ludwig tube characterization

For the freestream characterization process of the high-temperature Ludwig tube facility, a total of 38 tests were conducted in the Mach-8 configuration followed by 47 tests in the Mach-6.25 configuration. A range of fill pressures and hot-section temperatures were investigated throughout the characterization process; however, as most of these cases are qualitatively similar, only an illustrative example case is presented for each Mach number.

3.1 Mach-8 Characterization

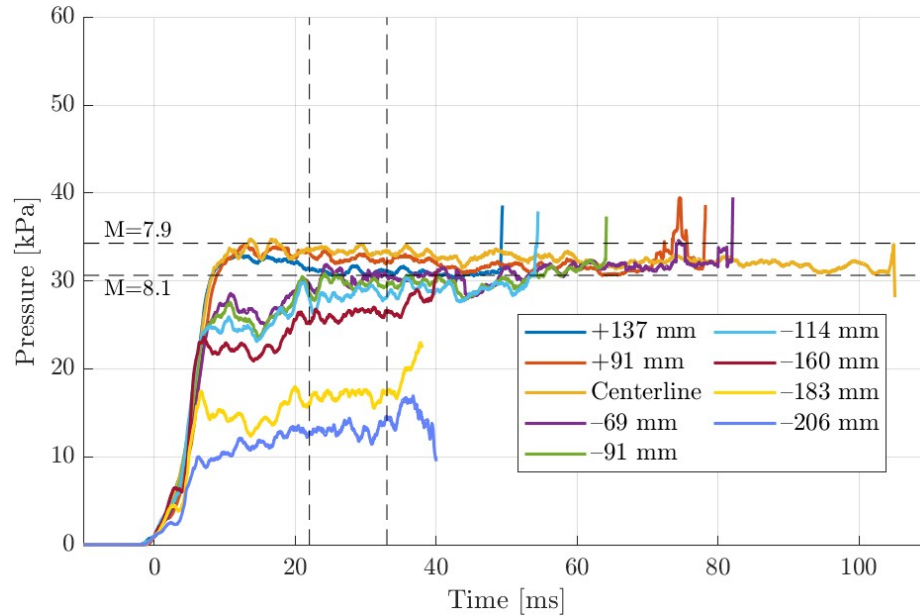


Figure 3.1: Typical Mach-8 Pitot pressure traces for $p_{Tube} = 40\text{ bar}$, $T_{hot} = 790\text{ K}$. Steady test time indicated by vertical dashed lines

The Pitot rake pressure traces for a typical test at Mach 8 with a charge-tube pressure of 40 bar and at hot-section temperature of 790 K is shown in Fig. 3.1. To reduce noise, a 251-point moving average filter was applied to the data. For additional clarity, the trace for a given probe is only plotted until it registers the unstart shock which manifests as a sharp spike in the pressure. From these traces, it can be seen that the flow startup time is approximately 20 ms. From roughly 10 – 25 ms, there is a gradual rise in the Pitot pressure measured by the transducers at y-locations of –69, –92, –115, and –161 mm. This slow rise and plateau indicate that these transducers are near the edge of the core flow and gives a core flow diameter of roughly 322 mm. The steady test time begins around 20 ms and last for ~15 ms before the unstart is first indicated by the probes at –183 and –206 mm. At probes closer to the centerline, it can be seen that steady flow is maintained for longer test times, with the centerline probe displaying steady test times greater than 80 ms. This trend is quantified in Fig. 3.2a which shows the mean steady test time versus radial position for all runs in this campaign. This implies that for a given test campaign, the steady test time will be a function of the size and shape of the test article, with usable test time decreasing as the model size increases. Note that the relatively early unstart for the Mach-8 configuration is thought to be at least partly caused by the inability to reach the desired vacuum levels with the facility’s current vacuum pump setup; steps will be taken to address this issue in the near future. Using the Rayleigh Pitot-tube formula,

$$\frac{p_{02}}{p_1} = \frac{(\gamma + 1)^2 M^2}{4\gamma M^2 - 2(\gamma - 1)} \frac{1 - \frac{\gamma}{\gamma - 1} + 2\gamma M^2}{\gamma + 1} \quad (3.1)$$

and assuming a calorically perfect gas, pressure traces such as those presented in Fig. 3.1 can be converted into Mach-number traces. Despite the high temperatures in the charge tube, the effects of vibrational excitation on the final freestream properties are negligible; therefore, the perfect gas assumption is valid for this application. Making this conversion

and considering only the steady test time for all tests results in the Mach-number distribution shown in Fig. 3.2b. This distribution shows a core-flow region of approximately 300 mm, consistent with the individual case depicted in Fig. 3.1. Additionally, Fig. 3.2b shows a region outside the core flow where the Mach number is greater than that in the core flow. This anticipated feature is due to the facility having a free-jet test section, the expansion that occurs as the flow exits the nozzle, and the pressure drop within the separated boundary layer that forms on the inside of the nozzle.

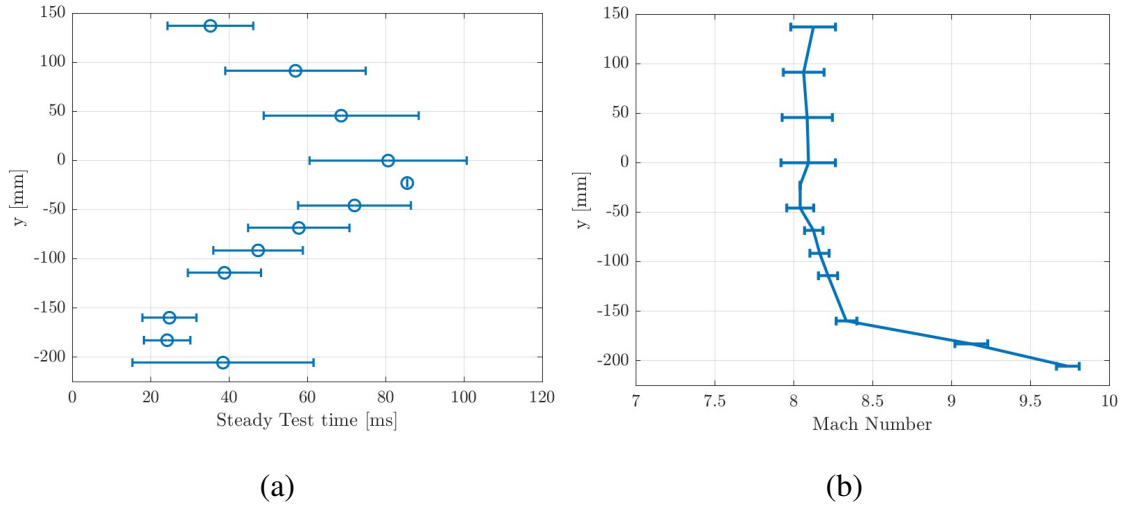


Figure 3.2: (a) Steady test time and (b) Mach-number distribution for Mach-8 nozzle over all tests. Error bars show one standard deviation.

For the FLEET measurements at Mach 8, a camera resolution of 46.6 pix/mm and a shortened write line of 28 mm was used, producing a read line with higher intensity. A shorter focal length allowed for sub-pixel molecular tracking at a higher accuracy; however, it also resulted in less extensive coverage of the core flow. For future use of FLEET in an air medium, a shorter focal length and higher pixel resolution is recommended. FLEET measurements showing the velocity distribution in the center of the flowfield are presented in Fig. 3.3 for three different operating temperatures. Velocity measurements are recorded during the steady test time and error bars indicate the temporal variation (one standard

deviation) in the measured velocity. These measurements show general agreement with the averaged velocities derived from the Pitot measurements (yellow line) measured over a larger portion of the core flow ($\pm 60 - 150$ mm). This is evidence that any wake generated as the flow from the charge tube passes around the fast-acting piston has minimal influence on the mean core flow for the Mach-8 configuration. Standard deviation of the velocity in the radial direction did not exceed 2% and can be considered negligible.

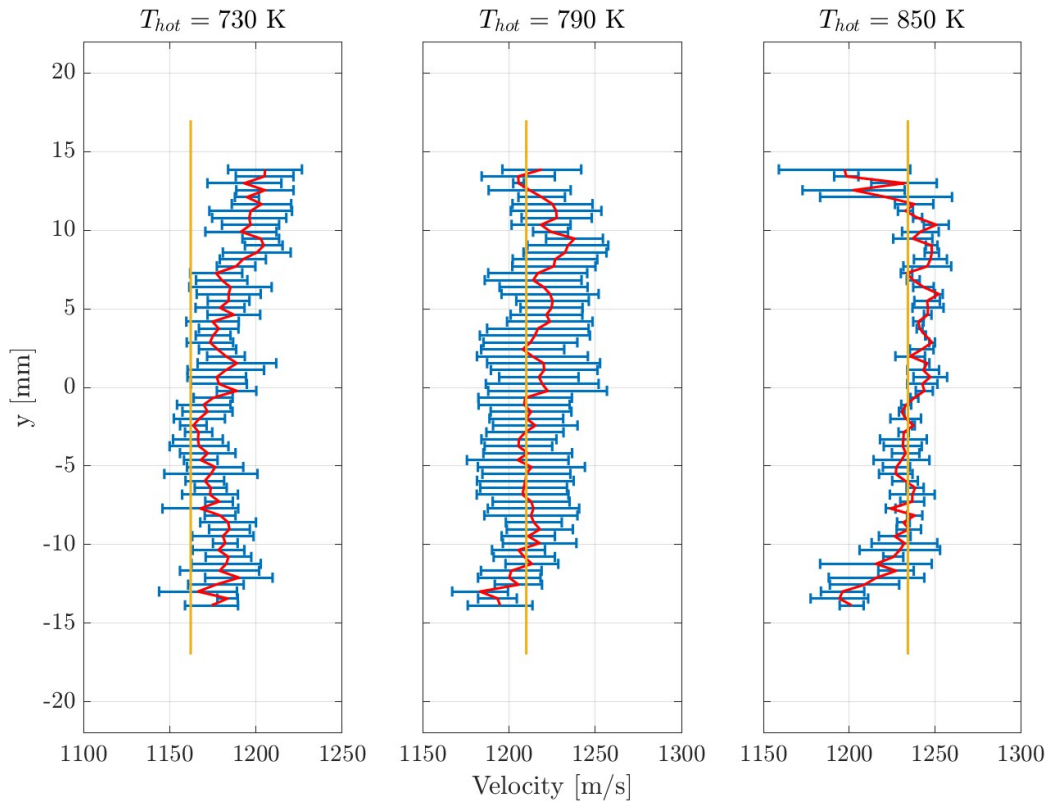


Figure 3.3: Velocity distribution during steady test time for Mach-8 nozzle over all tests at three hot-section temperatures. The yellow line indicates the mean velocity measured by the Pitot rake. Error bars show one standard deviation based on temporal variation.

3.2 Mach-6.25 Characterization

The Pitot rake pressure trace for a test at Mach 6.25 with a charge tube pressure of 30 bar and a hot-section temperature of 565 K is shown in Fig. 3.4. Again, to reduce noise,

a 251-point moving average filter was applied to the data. The flow startup takes place over approximately 15 ms whereas the steady test time is approximately 100 ms. This steady test time can be further broken down into two sections: from 15 – 55 ms where there are small variations in the Pitot pressure noticeable and from 60 – 115 ms where the Pitot trace is very steady. At ~ 120 ms, one sees the arrival of the reflected expansion wave which causes the drop in the measured pressure; this is shortly followed by the unstart shock, which is visible in the pressure spikes at ~ 145 ms. Although Fig. 3.4 shows only a single test case, this behavior was qualitatively identical over the entire range of operating conditions. The current data does not provide an estimate for the diameter of the core flow except that it is at least 184 mm in diameter. This Pitot survey is not comprehensive since a number of transducers were damaged during the Mach-8 calibration and were not able to be used for the subsequent calibration of the Mach-6.25 nozzle, yielding limited spatial resolution for the results presented herein.

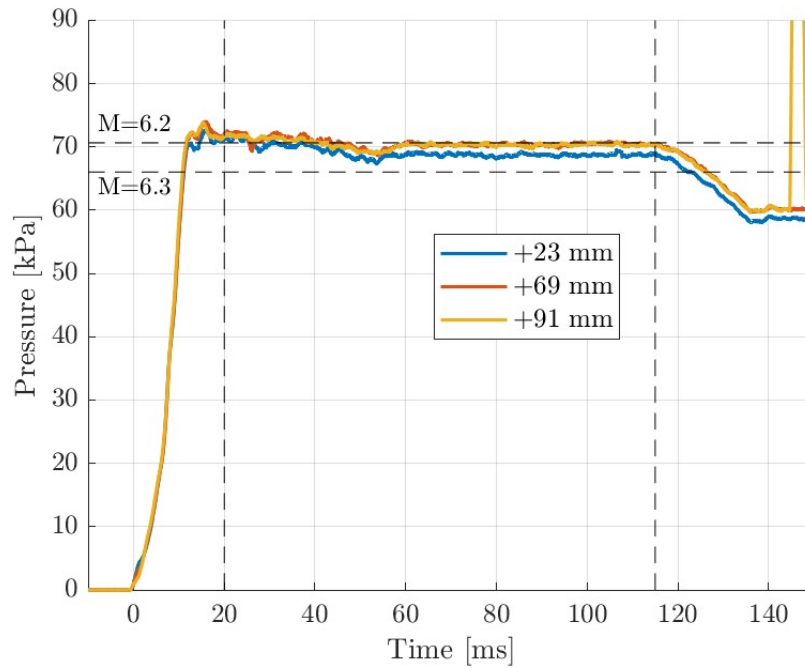


Figure 3.4: Typical Mach-6 Pitot pressure traces for $p_{Tube}=30$ bar, $T_{hot}=565$ K. Steady test time indicated by vertical dashed lines.

For the Mach-6.25 case, the end of the steady test time was chosen to be just before the arrival of the expansion wave. Figure 3.5a shows that, at the locations investigated, all transducers are experiencing steady test times > 90 ms. Note that the trend seen in Fig. 3.5a is that the steady test time closer to the centerline is shorter; however, this is most likely the result of statistical uncertainty due to the loss of several sensors during Mach-6.25 calibration. The same behavior as seen in the Mach-8 configuration is to be expected as more data is gathered. Finally, Fig. 3.5b shows the Mach-number distribution within the test section which agrees with the individual case presented in Fig. 3.4. Again, this does not provide an estimate of the complete diameter of the core flow, though we can conclude that the uniform Mach-number distribution over all working sensors implies that they are all within the core flow region.

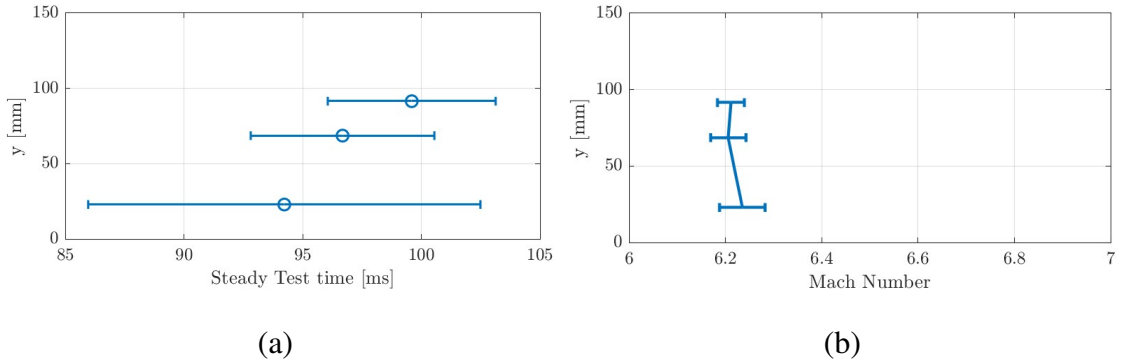


Figure 3.5: (a) Steady test time and (b) Mach-number distribution for Mach-6.25 nozzle over all tests. Error bars show one standard deviation.

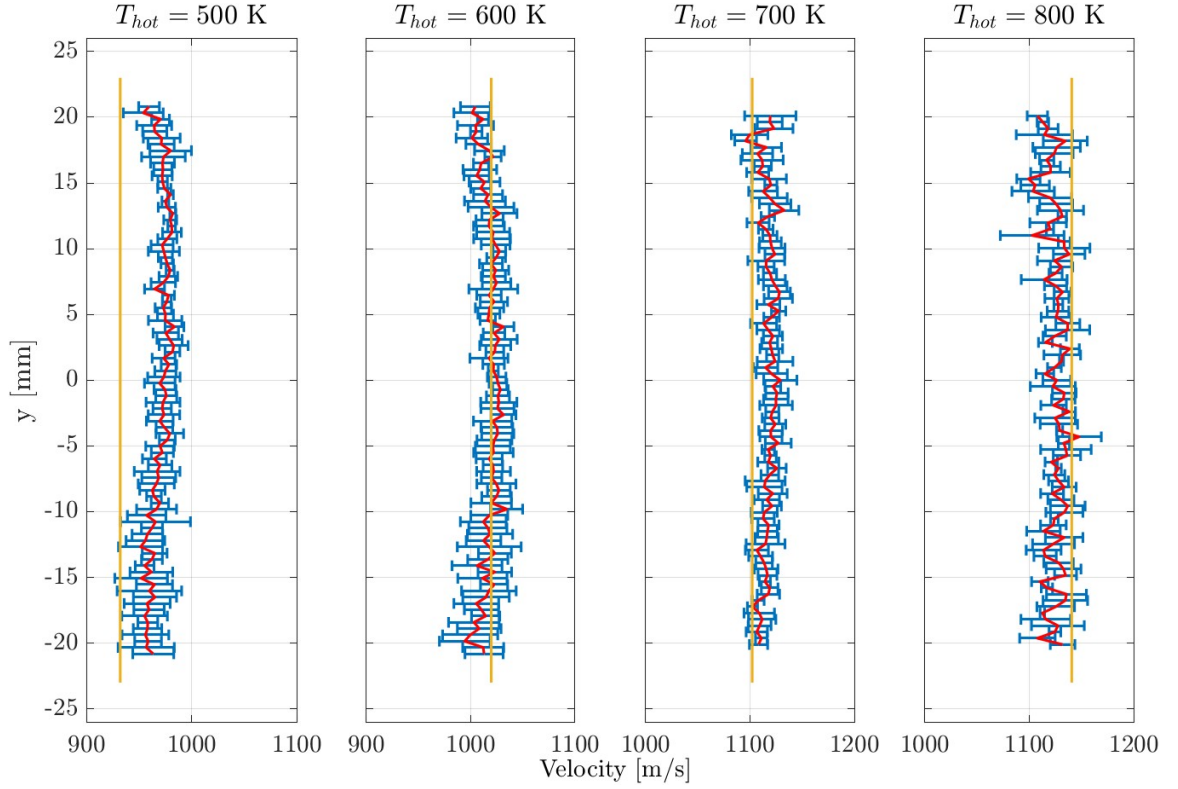


Figure 3.6: Velocity distribution during steady test time for Mach-6.25 nozzle over all tests at four hot-sections temperatures. Yellow line indicates mean velocity measured by Pitot rake. Error bars show one standard deviation.

FLEET measurements for Mach 6.25 were recorded at 21.3 pix/mm camera resolution with a 44 mm long write line. Due to the longer focal length of the write line at this Mach number, the read signal was significantly fainter than in the Mach-8 testing. Figure 3.6 shows the averaged velocity distribution for all tests at four distinct hot-section temperatures, with the error bars showing one standard deviation. Measurements at reservoir temperatures of 600 K and above show close agreement with the averaged Pitot rake velocities measured at the probe locations near the centerline. This is evidence that the suspected wake from the fast-acting piston does not have a significant effect on the mean core flow at Mach 6.25; however, the limited spatial resolution prevents a comparison as extensive as that for the Mach-8 measurements. As in the Mach-8 configuration, standard deviation of

the velocity in the radial direction did not exceed 2% and can be considered negligible.

3.3 Summary

The operating capabilities and a freestream characterization for the new high-temperature Ludwig tube at the University of Maryland at College Park were presented in example cases at Mach 8 and Mach 6.25. At Mach 8, a Pitot rake survey showed steady test times ranging from 40 – 80ms within the ~ 300 mm-diameter core flow. At Mach 6.25, this survey showed steady test times on the order of ~ 100 ms within a core flow which is at least 184mm in diameter. Both of these Pitot rake surveys were corroborated by FLEET velocimetry measurements which provided an independent measurement of the flow velocity and showed no evidence of the presence of a wake generated by the fast-acting piston used to initiate the flow upstream.

Chapter 4: Transitional Case

4.1 Undisturbed boundary layer

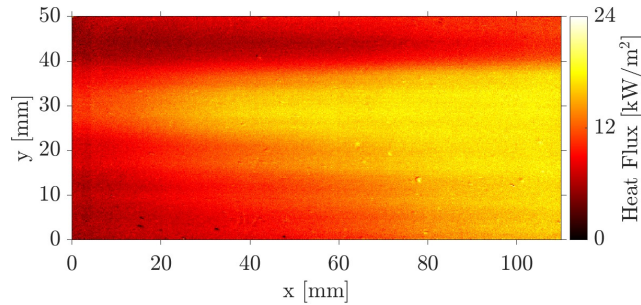


Figure 4.1: Mean heat-flux distribution for the no-fin case (Condition A, Delrin).

First, to determine the state of the incoming undisturbed boundary layer, measurements were performed with no fin attached. A TSP-derived heat-flux distribution for condition A is shown in Fig. 4.1 with the flow left to right; qualitatively similar results were obtained at conditions B and C. The upstream part of the heat-flux distribution exhibits a substantial positive gradient in the streamwise direction, implying that the flow state is transitioning to turbulent in this region. Additionally, there is a clear spanwise non-uniformity with transition occurring farther upstream between $y = 25$ mm and $y = 40$ mm and significantly farther downstream between $y = 40$ mm and $y = 50$ mm. Further inspection revealed that such a nonuniform transition front was present in a majority of the runs within this investigation. This is most likely the result of imperfections in the leading edge of the flat plate, perhaps caused by the impact of diaphragm fragments. This is a problem known to affect

experiments in facilities of this type, such as those conducted in the HEG reflected-shock wind tunnel by Laurence et al. [60], where a similar non-uniform transition front on a sharp-leading edged ramp with sidewalls was observed.

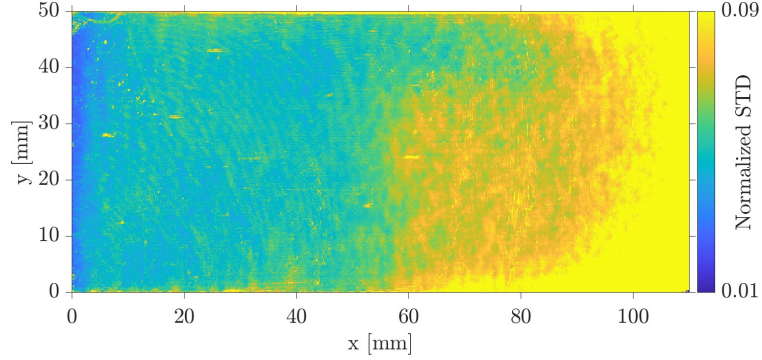


Figure 4.2: Normalized STD map for no-fin case (Condition A).

These streamwise trends are also visible in the plan-view high-speed schlieren as visualized in Fig. 4.2; here, the standard deviation (STD) at each pixel location normalized by the mean signal over the steady test time at that location is shown for condition A (typical images used to produce this distribution are shown in Fig. 4.6). This STD metric is used throughout the present work as a measure of the pixel-wise fluctuation intensity in the schlieren images. This mapping shows that an abrupt change in the fluctuation intensity comes at approximately $x = 60\text{ mm}$ in the lower part of the window (i.e. $y < 40\text{ mm}$). Similar to the TSP results, in the region where $y > 40\text{ mm}$, there is evidence of delayed transition; however, the early transition between $y = 25 - 40\text{ mm}$ seen in the TSP results does not clearly manifest itself in the STD distribution. Farther downstream, at $x \approx 90\text{ mm}$, there is a further increase in the fluctuation intensities which may be indicative of the full onset of turbulence. This provides further evidence that the boundary layer under consideration is transitional within the region of interest.

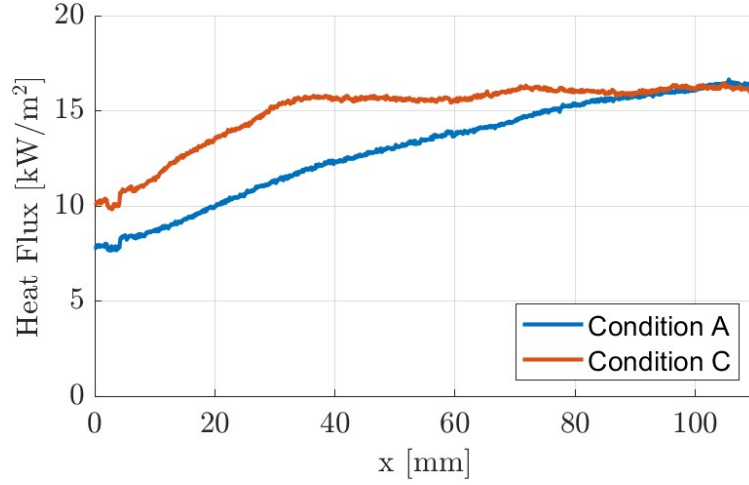


Figure 4.3: Mean spanwise heat-flux for no-fin case.

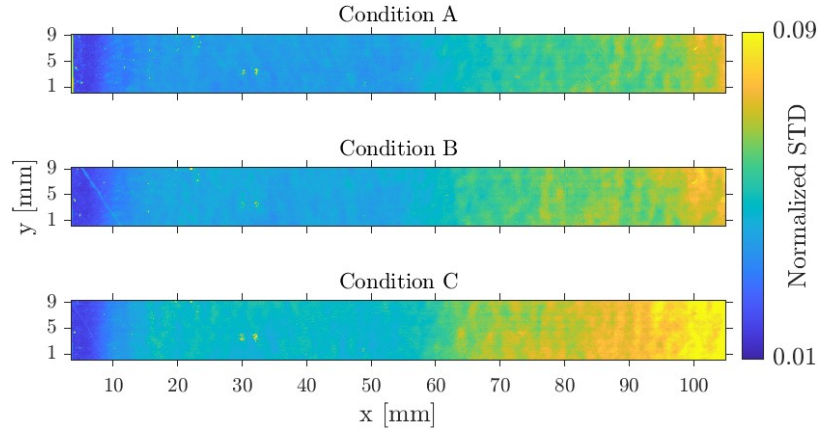


Figure 4.4: Comparison of normalized STD maps over all tunnel conditions.

The influence of the different tunnel conditions can be seen in the span-averaged heat-flux profiles for the undisturbed boundary layer for conditions A and C in Fig. 4.3. These curves show the mean heat flux over the steady test time averaged over the entire span for a given x -location. The important distinction between the conditions is that the heat flux for condition C reaches a plateau much further upstream than the heat flux for condition A. This implies that the boundary layer of condition C transitions to turbulence earlier, as would be expected for the higher unit Reynolds number associated with that tunnel condition. The effect of the different tunnel conditions can also be seen in the STD maps in Fig. 4.4. The

most apparent difference between the flow conditions is the downstream point at which the maximum STD value is reached. For conditions A and B, this happens at roughly $x = 105$ mm (i.e. the farthest downstream portion of the field of view), whereas for condition C, this point is reached slightly earlier, in the vicinity of $x = 90 - 100$ mm. Despite the variation in the location at which this maximum value is reached, it is also notable that each condition sees a relatively sharp increase between $x = 60 - 70$ mm when compared to the upstream STD value. Finally, though more subtle, one can also see a progressively higher mean STD farther upstream, as early as $x = 10$ mm, as the Reynolds number is increased; this is consistent with the increased flow density at these higher Reynolds numbers. Note, for both Fig. 4.2 and 4.4, the reduced STD value at the most upstream end of the field of view is an artifact of the experimental setup and is not physical.

4.2 General observations of SWBLI

First, to demonstrate the ability of the employed TSP to resolve changes in heat flux on short time scales, in Fig. 4.5 we show a sequence of heat-flux distributions derived during flow start-up. During this time, the flow conditions are changing rapidly and the SWBLI flow over the fin is being established, leading to large temporal variations in the surface heat flux. The spacing between consecutive images shown is 0.067 ms, i.e., they are two time steps apart. We note substantial image-to-image changes in the heat flux, most notably in the peak heating zone near the fin leading edge, but also in the SWBLI-affected region further downstream. While this does not provide a formal quantification of the effective temporal response, it nevertheless gives a qualitative indication that the TSP technique is capable of resolving changes in heating levels on time scales of ~ 0.1 ms or better.

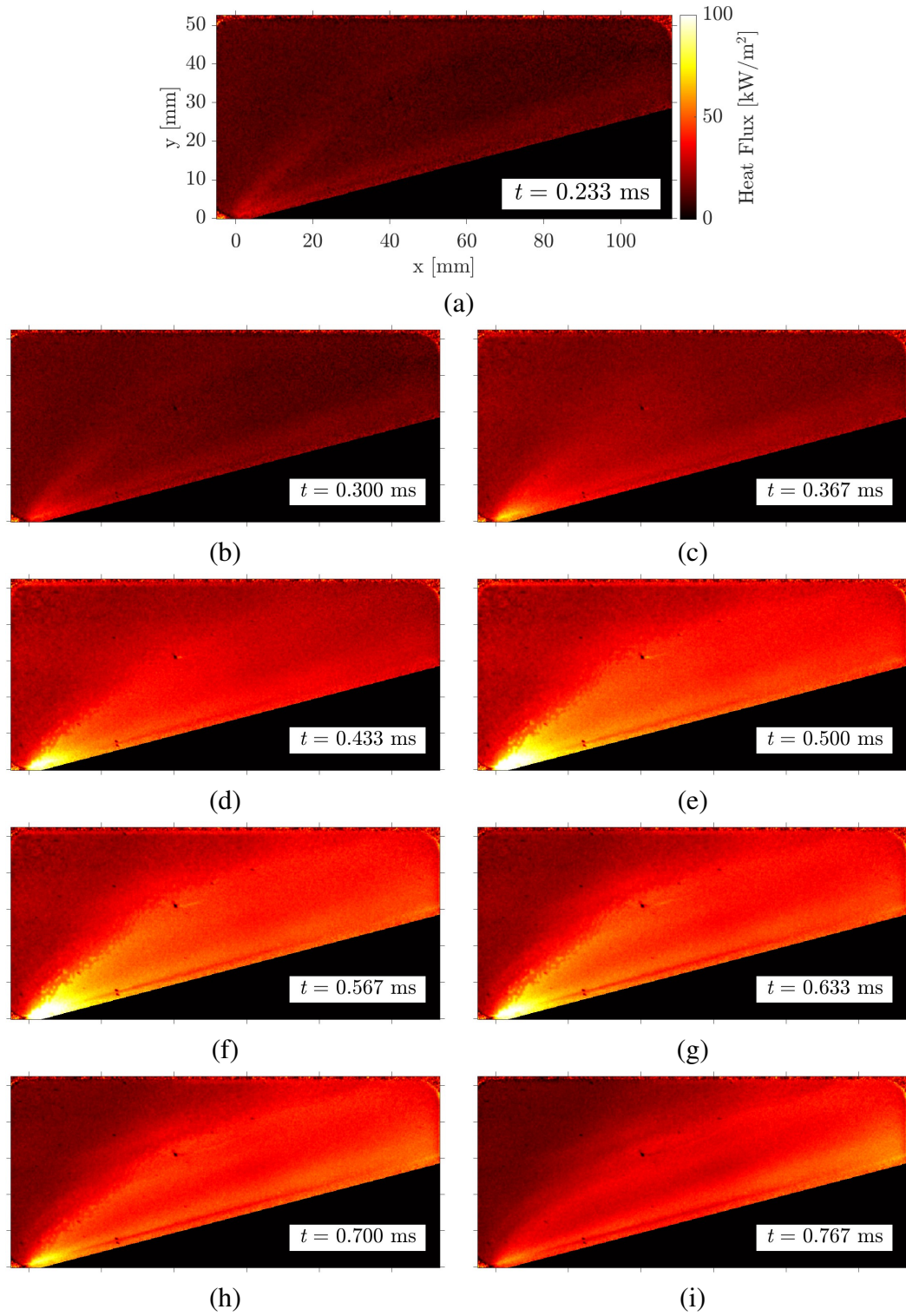


Figure 4.5: Time-resolved TSP heat-flux distributions during tunnel startup for the 15° case (Condition A, Delrin).

4.3 Time-averaged behavior

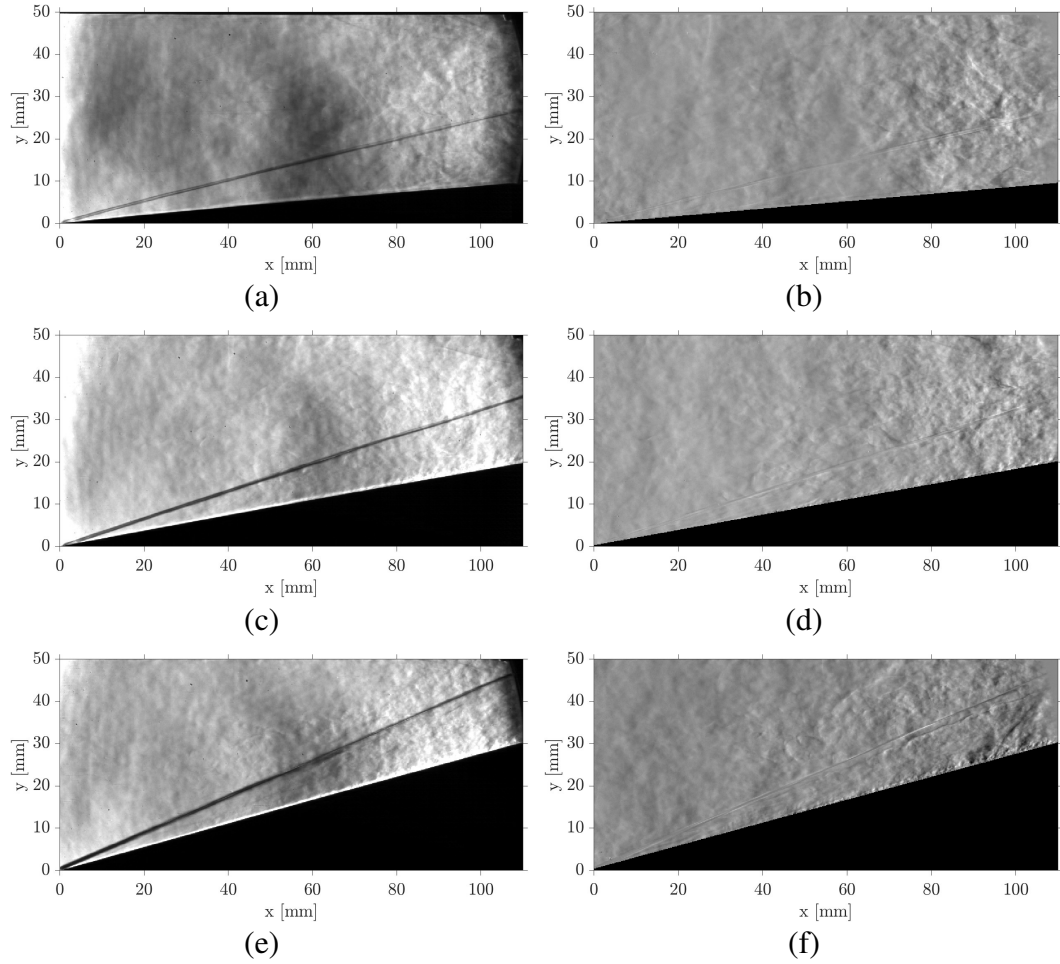


Figure 4.6: Example of raw (a, c, e) and reference-subtracted (b, d, f) schlieren images for each deflection angle (Condition A).

To demonstrate the main schlieren features for the various fin angles, Fig. 4.6 shows both raw and reference-subtracted instantaneous images from condition A, in each case taken from the steady test time. The coordinate origin here (and hereinafter) is centered at the fin leading edge. The raw images in Fig. 4.6a, 4.6c, and 4.6e depict prominent flow features, in particular the main inviscid shock wave. The processed images in Fig. 4.6b, 4.6d, and 4.6f were created by subtracting a reference image, generated by averaging a se-

quence of images captured directly before and after. In essence, this reference subtraction removes lower-frequency flow features in the image and emphasizes instantaneous structures, particularly those associated with transition and turbulence. Several flow features can be discerned in the reference-subtracted images that are not so readily found in the raw schlieren. One example is the boundary layer on the surface of the fin, which can be seen transitioning to turbulence at approximately $x = 65$ mm and $x = 55$ mm for the 10° and 15° cases, respectively. Another feature is an area of increased activity in the form of turbulent structures outside the shock in the center of the field of view, which is consistent with the transitioning of the flat-plate boundary layer. It is not immediately clear from these instantaneous images, however, whether this transition is at all accelerated by the presence of the SWBLI.

The normalized schlieren STD mapping for each angle of attack is plotted in Fig. 4.7a, 4.7c, and 4.7e for condition A; results at the other tunnel conditions were qualitatively similar. Several features can be noted as the flow progresses through the SWBLI. First, the STD fluctuation intensities in the region inboard of the shock wave are consistently higher than for the flow outboard of the shock. There is also a region outside the shock wave with elevated levels compared to the surrounding flowfield starting around $x = 50$ mm for each case; however, this is likely caused by the region of early transition, considering its consistent presence and similarity between cases. Along the fin, the inception region does not display fluctuation intensities notably different than in the undisturbed freestream, with levels remaining relatively constant until $x \approx 50$ mm for each angle of attack. Further downstream, streak-like patterns aligned with the fin are visible between the shock and fin surface for the 10° and 15° cases. In the farthest downstream portion of the region of interest, the final amplitude reached appears to be the same irrespective of whether or not the flow passed through the SWBLI. Furthermore, this final value appears to be of the same magnitude for each angle of attack and is reached at the same distance downstream.

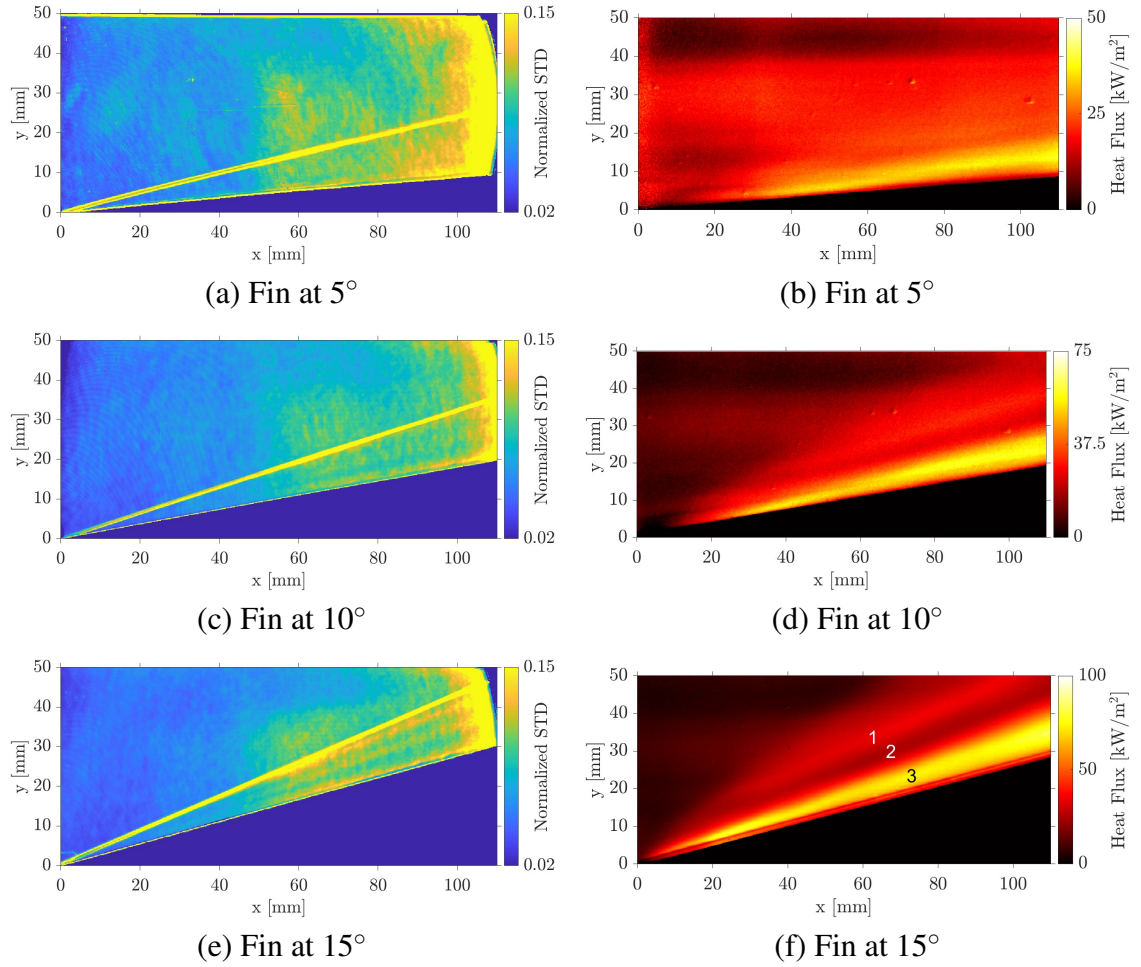


Figure 4.7: Normalized STD (a, c, e) and mean heat-flux measurements (b, d, f) (Condition A, Delrin).

Figures 4.7b, 4.7d, and 4.7f show the heat-flux distributions for each angle of attack at condition A; again, the corresponding distributions for conditions B and C showed no qualitatively significant differences. For each case, the heat flux is relatively low within the unaffected freestream, then, moving inboard, reaches an initial peak (referred to as the "secondary peak" – labelled 1 in Fig. 4.7f), a local minimum (2), the primary peak (3), and finally a slight decrease directly adjacent to the fin. This pattern is accentuated as the deflection angle of the fin is increased, being barely discernible at 5° and clearly apparent at 15°. The overall heat-flux levels also grow substantially as the fin deflection

angle is increased. This suggests that, like other flow properties of this SWBLI, the level of heating scales with normal component of the Mach number, M_n , or the inviscid shock strength, p_2/p_1 . The mean heat flux along the primary peak (i.e. the maximum heat flux of the interaction) is plotted against M_n for every test at all tunnel conditions in Fig. 4.8. From this figure, it is clear that the peak heating value scales with M_n ; however, there are insufficient data points to deduce a clear correlation. One somewhat surprising observation is that the maximum heat flux does not show an increasing trend with Reynolds number for a given fin angle. One possibility is that the interaction of the transition process with the SWBLI is complicating any tendencies that would otherwise be present.

Although the peak-trough-peak heating distribution observed here has been found in previous studies of turbulent SWBLIs [8, 26, 27, 40, 44], the global measurement provided by the TSP gives a much clearer picture of the heat-flux distribution. Notably, the shape and relative intensity of the heat flux appears to be rather consistent over the angles of attack under consideration. This is not necessarily to be expected since it has been established that the flow structures of this interaction progress through several different regimes as M_n increases. Recall, Alvi and Settles [5] found that the flow topology progresses from an interaction where only primary separation occurs for $1.2 < M_n < 1.5$ to one where secondary separation is present for $M_n > 1.5$. As the interaction strengthens further, a "normal shock" forms within the impinging jet at $M_n > 1.9$ and supersonic reverse flow begins at $M_n > 2.1$. Since $1.38 < M_n < 2.35$ for the present tests, one would expect a progression through several of these regimes as the angle of attack is increased, i.e., all should experience incipient separation, as $M_n > 1.2$, but only some should reach secondary separation, "normal shock" formation, or supersonic reverse flow. Therefore, the consistency in the shape and amplitude of these heat-flux distributions over the range of interaction strengths investigated is a notable result.

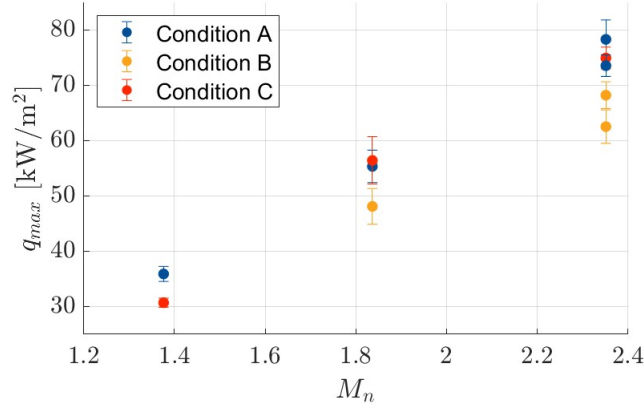


Figure 4.8: Scaling of maximum heat flux in the SWBLI against normal component of Mach number. Error bars show one standard deviation.

4.4 Quasi-conical symmetry

Knowing that flow features of such SWBLIs in the laminar and turbulent cases exhibit a conical symmetry about a virtual conical origin (VCO) [14], it is also of interest to ask whether such symmetry is also present in the transitional case studied here, in particular as associated with the surface heat-flux distribution. For the turbulent case, Rodi and Dolling [8] found that the surface heating was not conically symmetric in that there was no VCO based upon the heat-flux features about which these features collapsed when normalized by the undisturbed value at the interaction edge. Moreover, it was found that, along rays emanating from the VCO based on pressure features, the heat transfer did not decay at the $1/r$ rate that would be indicative of conical symmetry (since $q \propto \partial T / \partial y$).

In the present case, the first step in assessing the degree of conical symmetry is identifying the approximate location of a hypothetical VCO in the heat-flux distribution, VCO_q . The following procedure was developed and is summarized in Fig. 4.9.

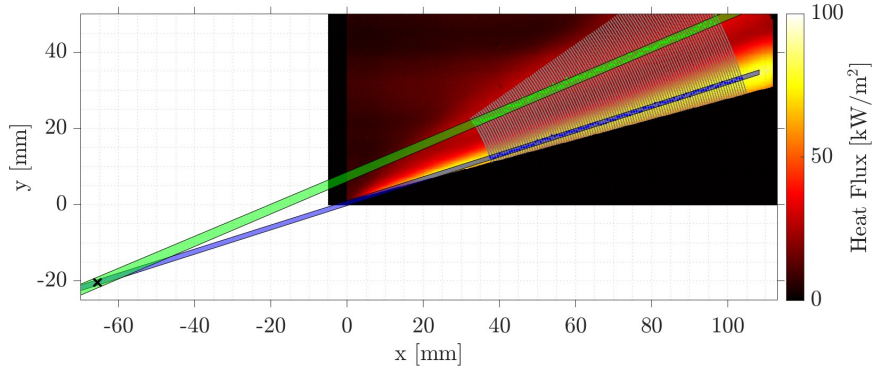
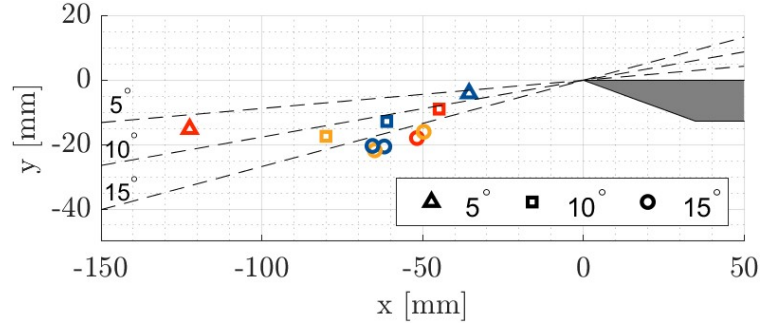
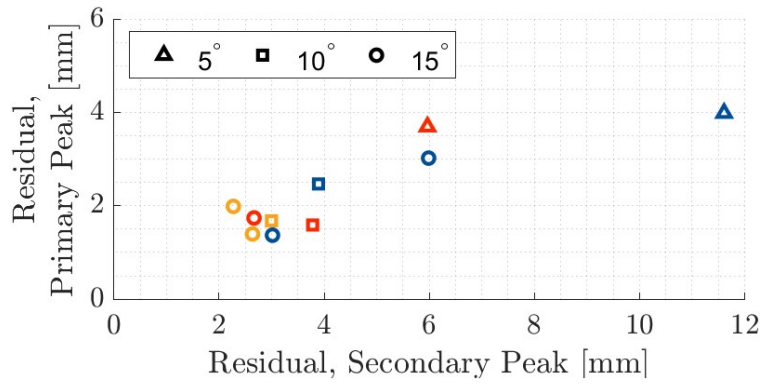


Figure 4.9: Example of linear regressions used to find location of the virtual conical origin.

The downstream portion of the region of interest was first meshed with a grid of circular arcs (gray in Fig. 4.9) which was centered about the leading edge of the fin. Along every arc of this grid, the heat flux at each azimuthal location was extracted, yielding an array of heat-flux values for each radial distance. Each of these arrays was then smoothed using a robust quadratic regression to eliminate noise in the data and leave only the characteristic shape of the distribution. Next, the two most prominent peaks, corresponding to the primary and secondary peaks previously described, were selected from the smoothed distributions (blue/green dots) in Fig. 4.9. Once this was done for each radial distance, a linear regression through each set of peaks was calculated; in Fig. 4.9, this is depicted as the blue/green regions shaded between $y \pm 2\Delta$ where y is the fit-line and Δ is the standard error for prediction. By following these regressions and extrapolating to where they intersect, the approximate location of the VCO_q was determined ($\times$). About this newly determined VCO_q , a subsequent grid of arcs and rays was generated. Although this process can be iterated, iteration showed no evidence of convergence towards a final VCO_q location; therefore, this process was only applied once.



(a)



(b)

Figure 4.10: Scatter plot of VCOs from all tests at all conditions (a) and residuals of linear regressions along primary and secondary peaks (b). Note: coloring scheme same as Fig. 4.8; fin shown in (a) at $\alpha = 0^\circ$ for reference.

A scatter plot of the VCO_q locations determined in all TSP experiments is presented in Fig. 4.10a (note that some combinations of fin angle and tunnel condition were repeated). For the 15° case, the VCO_q locations are grouped closely together, though we observe increased scatter for 10° , and the two points for 5° are widely dispersed. The reduced heat fluxes, and thus higher relative noise, for smaller angles leads to a higher uncertainty in the peak locations. We also note that, since the two lines have only a small angular separation, even a small uncertainty in slope can lead to relatively large uncertainties in the VCO location, especially in the radial direction. This uncertainty is quantified in Fig. 4.10b which shows the residuals for the regressions along the primary and secondary peaks.

As a whole, Fig. 4.10a shows a general trend for the approximate location of a VCO_q determined here to be different to that of the VCO based on previous measurements for laminar and turbulent SWBLIs in the literature. In every case, the VCO_q location was found to lie away from the extension of the inviscid shock trace, a feature known to run through the classically determined VCO. Instead, it appears that the VCO_q lies between the extension of the shock trace and an extension of the face of the fin (shown by dashed lines in Fig. 4.10a). This suggests that there is a discrepancy between the VCO location determined by heat-flux measurements versus other surface quantities or flow features, and/or the transitional nature of the SWBLI in the present experiments may result in a VCO location different to that of the fully turbulent case.

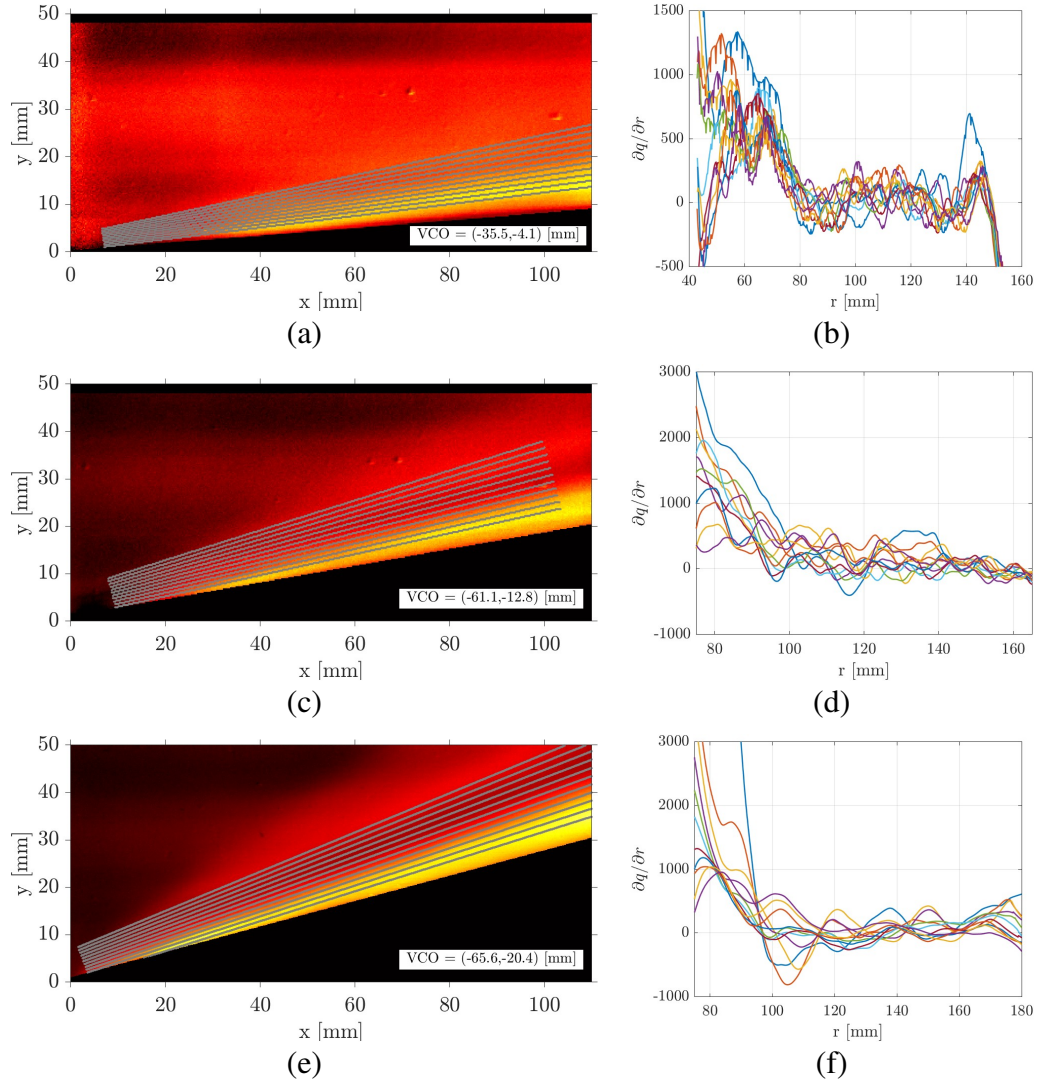


Figure 4.11: Radial derivatives of heat-flux distributions along rays originating at VCO (Condition A, Delrin).

The global heat-flux measurement provided by the TSP also permits a direct investigation into the inception length of the SWBLI. From the VCO_q , a series of rays, as shown in Fig. 4.11a, 4.11c, and 4.11e, were generated spanning the entirety of the region of interest. Along these rays, the heat flux was extracted and smoothed using a robust quadratic regression, and the numerical derivative of the heat flux in the direction of the ray, $\partial q / \partial r$, was calculated. When plotted against the radial distance from the VCO_q , as in Fig. 4.11b, 4.11d,

and 4.11f, an estimate for the length of the inception zone, within which the heat flux exhibits substantial variations along rays, could be made. Despite some residual variation remaining further downstream, the inception zone can be relatively well distinguished from the conically symmetric region for each angle of attack. Specifically, the inception zone ends at approximately $r = 85$ mm, $r = 100$ mm, and $r = 115$ mm for the 5° , 10° , and 15° cases, respectively. Some caution should be exercised in comparing results here, however, since the uncertainty in the VCO_q location, particularly for 5° , is large, and we have already noted that the VCO_q locations determined from the heat-flux distributions appear to differ from those determined using other means.

To assess the degree of conical symmetry in the present flowfields, in Fig. 4.12 we show the heat-flux profiles along a collection of rays and arcs (with the determined VCO_q as the origin) downstream of the inception region for the three fin angles at condition A. In Fig. 4.12d, 4.12f, and 4.12h, the heat flux is plotted against the normalized angle from the fin, $\theta' \equiv (\theta - \alpha)/(\beta - \alpha)$, where α is the fin angle and β is the shock-wave angle; this provides a quantitative depiction of the patterns described previously. All runs exhibit a primary peak slightly offset from the fin surface, with a minimum and secondary maximum further away from the fin for the stronger interactions at 10° and 15° . Also, the influence of the non-uniform transition front observed in Fig. 4.1b, i.e., in the undisturbed flat-plate boundary layer, can be seen in the differing final values that are encountered for each case at high values of θ' . The prominence of the secondary peak, or lack thereof, at 5° is possibly due to different flow structures present (since $M_n < 1.5$ and therefore we do not expect a secondary separation region to form), as mentioned previously. This lack of a prominent secondary peak is also the primary reason for the scattered VCO locations and large residuals seen in Fig. 4.10.

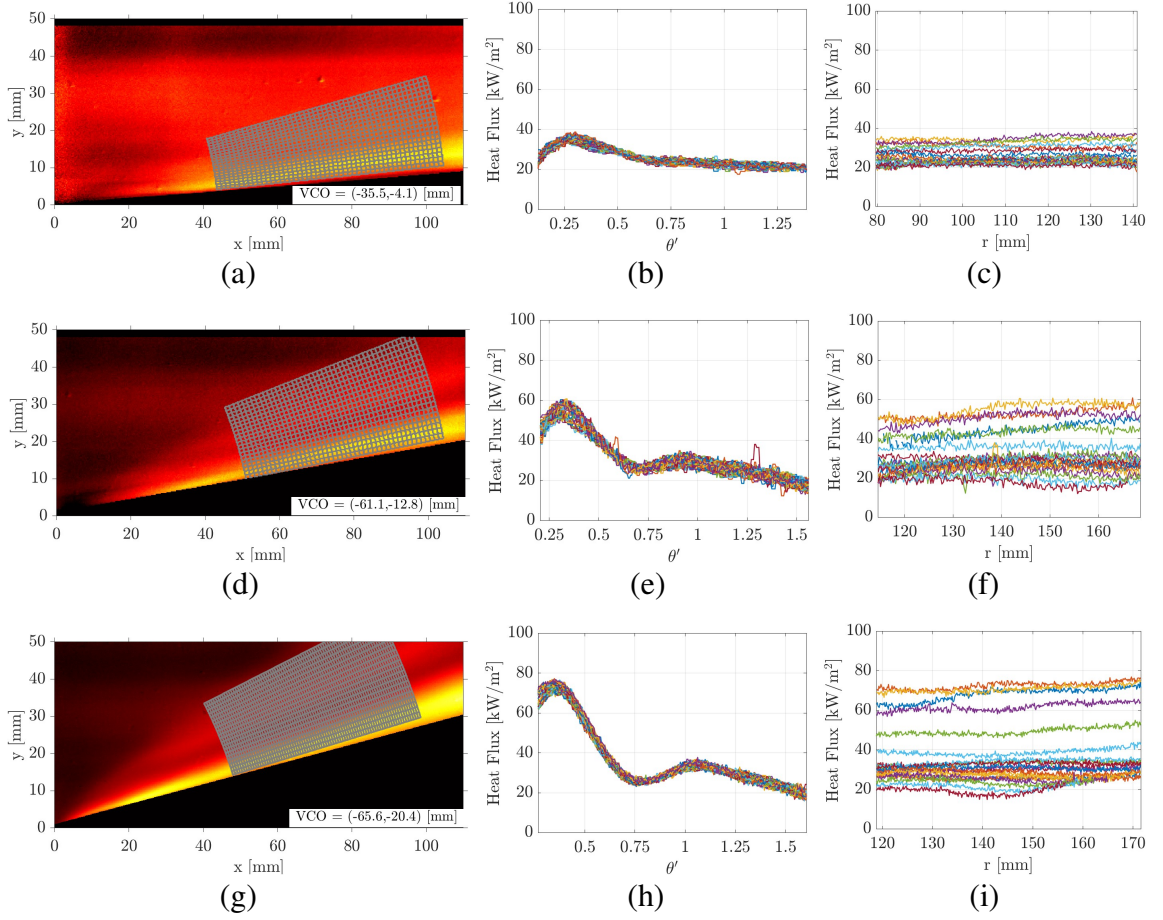


Figure 4.12: Mean heat-flux variation along arcs of constant radius from VCO (b, e, h) and rays of constant angle (c, f, i) for fin deflection angles of 5° (a), 10° (d), and 15° (g), respectively (Condition A, Delrin).

Comparing fin angles, the primary peak occurs around $\theta' = 0.28$ for the 5° case and $\theta' = 0.35$ for the 10° and 15° cases. For the trough, as the interaction strength increases, its angular location tends towards slightly larger values, it does not appear for the 5° case, then is at $\theta' = 0.7$ for the 10° case, and finally $\theta' = 0.75$ for the 15° case. The secondary peak displays a similar behavior, not appearing in the 5° case and lying at roughly $\theta' = 0.93, 1.05$ for the later two cases.

Referring to Fig. 4.12c, 4.12f, and 4.12i, where in each case the time-averaged heat fluxes along rays of constant θ are plotted, in most cases the heat flux remains largely con-

stant along a given ray. This consistency provides further evidence that the region being analyzed is not being influenced by the fluctuations of the inception region. Moreover, the collapse of curves along arcs in Fig. 4.12b, 4.12e, and 4.12h with the relative constancy along rays in Fig. 4.12c, 4.12f, and 4.12i implies that the symmetry observed not only applies to the location of the characteristic flow features but also to the magnitude of the heat fluxes. Although this has been observed previously for a turbulent boundary layer [40], one might not intuitively expect a symmetry of this nature to exist for an incoming transitional boundary layer that exhibits significant variations in the streamwise direction. Indeed, even in the laminar or transitional cases, the growing boundary-layer thickness might be expected to lead to variations in the magnitude of the surface heat flux. Previous works [8, 39, 40] have concluded that the heat-flux distributions generated by a fin-induced SWBLI do not obey the same conical symmetry observed by the other features of this flowfield in the strict sense that q does not exhibit a decay with $1/r$ when normalized. In the present case, Fig. 4.12 provides strong evidence of quasi-conical symmetry in terms of the raw amplitudes and heat-flux distribution in this class of transitional SWBLIs.

A similar approach can be applied to the schlieren data to produce a PSD estimate along circular arcs centered about the VCO. This can be seen for several radii for $\alpha = 15^\circ$ in Fig. 4.13. From this mapping, one can see there is a consistent azimuthal value of $\theta' \approx 2.5$ above which there is a significant drop off over a broad range of frequencies; the location of this drop is likely indicative of the line of upstream influence. There is also a broadband peak just inboard of the inviscid shock at $\theta' \approx 0.9$. This peak appears to grow in relative intensity for larger radii and is possibly indicative of the growing separation vortex. The boundary layer that forms on the surface of the fin also generates a peak directly adjacent to the fin, which is where the highest PSD amplitudes in the data considered are found. Otherwise, excluding the inviscid shock wave at $\theta' \approx 1$, Fig. 4.13 does not exhibit any significant spectral features which suggest a correspondence with anticipated flow features.

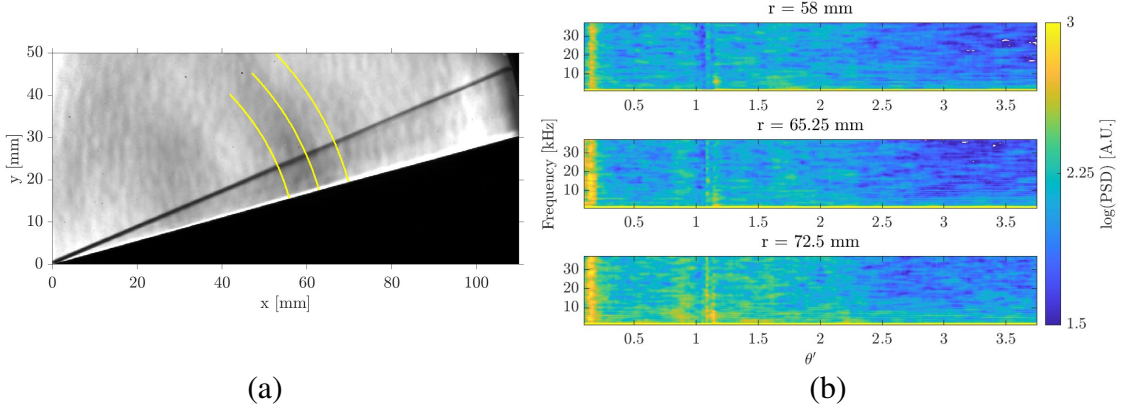


Figure 4.13: Sampling locations (a) used to generate PSD mappings (b) (Condition C).

4.5 Unsteady SWBLI behavior

By extracting time-resolved data during the steady test time and focusing only on a single grouping of pixel locations, we can gain a better picture of the degree of unsteadiness present in the surface heat-flux distribution. Note that the temporal response of the TSP methodology employed here is not sufficient to resolve rapid variations from, e.g., instantaneous turbulent structures, but can nevertheless give a picture of the motion of large-scale flow features. Figure 4.14c shows the time-varying heat flux along the arc indicated in Fig. 4.14a. In absolute terms, we note a similar amount of unsteadiness over the entire sweep of the arc. Relative to the amplitude of the peaks, this unsteadiness is much more significant along the secondary peak than along the primary peak. Likewise, Fig. 4.14d shows the variation in time along the ray shown in Fig. 4.14b, and we observe a significant difference between the section of the ray within the inception region and that where conical similarity is expected. Specifically, the inception region appears to be characterized by higher mean and unsteady amplitudes compared with the region between $r = 120 - 150$ mm (note the arc in Fig. 4.14a is located at $r = 132$ mm). However, it is also clear that unsteadiness is once again elevated in the far downstream region where $r > 160$ mm. This

may be linked to the influence of the boundary-layer transition on the surface of the fin spreading outboard as can be seen in Fig. 4.6.

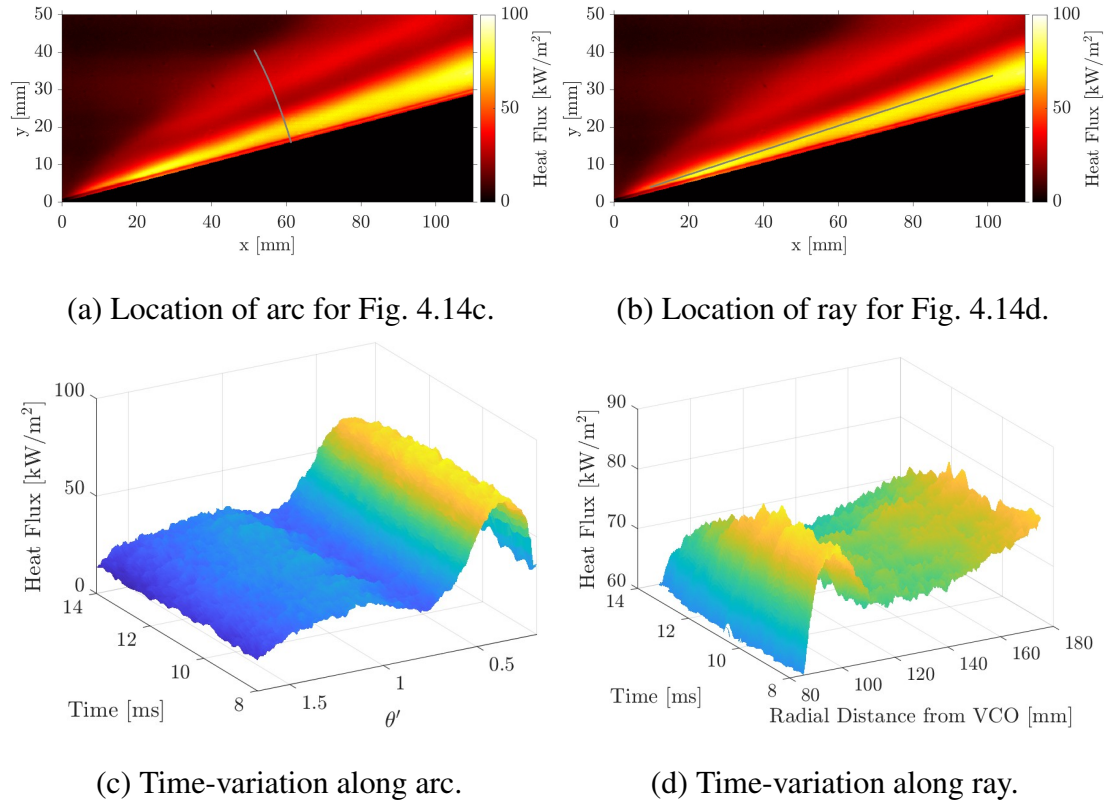


Figure 4.14: Arc and ray location with respective time-variation in heat flux (Condition A, Delrin).

An alternative, more global way of viewing the unsteadiness of the heating is presented in Fig. 4.15, which shows the absolute and normalized variances of the heat flux over the steady test time. Figure 4.15a reinforces the results seen in Fig. 4.14 and emphasizes the high levels of absolute variation seen in the inception region, especially along the primary peak. Figure 4.15b shows that, relative to the magnitude of the mean heat flux in that location, the secondary peak also experiences high levels of unsteadiness. Both plots display a rather steady region close to the fin in the intermediate downstream region ($x = 50 - 100\text{mm}$). These data can also be used to estimate the line of upstream influ-

ence. Unlike the mean heat-flux distribution presented in Fig. 4.7, which shows a gradual rise from the unaffected freestream, in Fig. 4.15a there is a distinct boundary demarcating the beginning of the interaction. This line runs from near the origin to approximately $x \approx 56$ mm and $y \approx 39$ mm, which corresponds to an angle of $\beta_{UI} \approx 32.4^\circ$. This value is consistent with that observed in the schlieren analysis presented in Fig. 4.13.

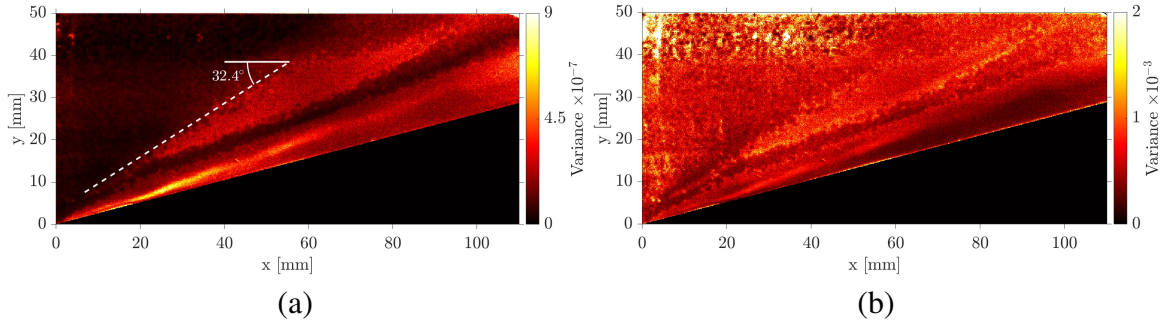


Figure 4.15: Absolute variance (a) and variance normalized by mean heat-flux (b) (Condition A, PEEK).

The schlieren data allow us to examine the unsteadiness present at higher frequencies than the TSP. Figure 4.16a provides a mapping of the spectral energy within the range 150 – 160 kHz over the entirety of the visualized flowfield. Note that, in this sequence, the camera was rotated to align with the fin: x' and y' are the distances from the fin leading edge in this rotated frame. To create this mapping, a time series was extracted for each pixel in the raw schlieren over the steady test time. Pixel-wise power spectral densities (PSDs) were then created using Welch's method for a signal of length 2500 with a Hamming window of length $1562.5 \mu\text{s}$ and 50% overlap. The specific frequency range used to generate this mapping was 150 – 160 kHz as this was the highest frequency band available for the given frame rate; however, the results from other frequency ranges are nearly identical. First, note that in the inception region there are relatively low levels of spectral content, consistent with the normalized STD mapping presented in Fig. 4.7. These amplitude begin to rise around $x' = 40$ mm, with further growth occurring downstream; there are no clear boundaries, but

overall level do appear to be higher behind the shock wave. The highest intensities within the field of view occur within the fin boundary layer; however, it is important to recall that the line-of-sight integration of the schlieren through the fin boundary layer is much longer than for the flat-plate boundary layer, which may be skewing their relative amplitudes.

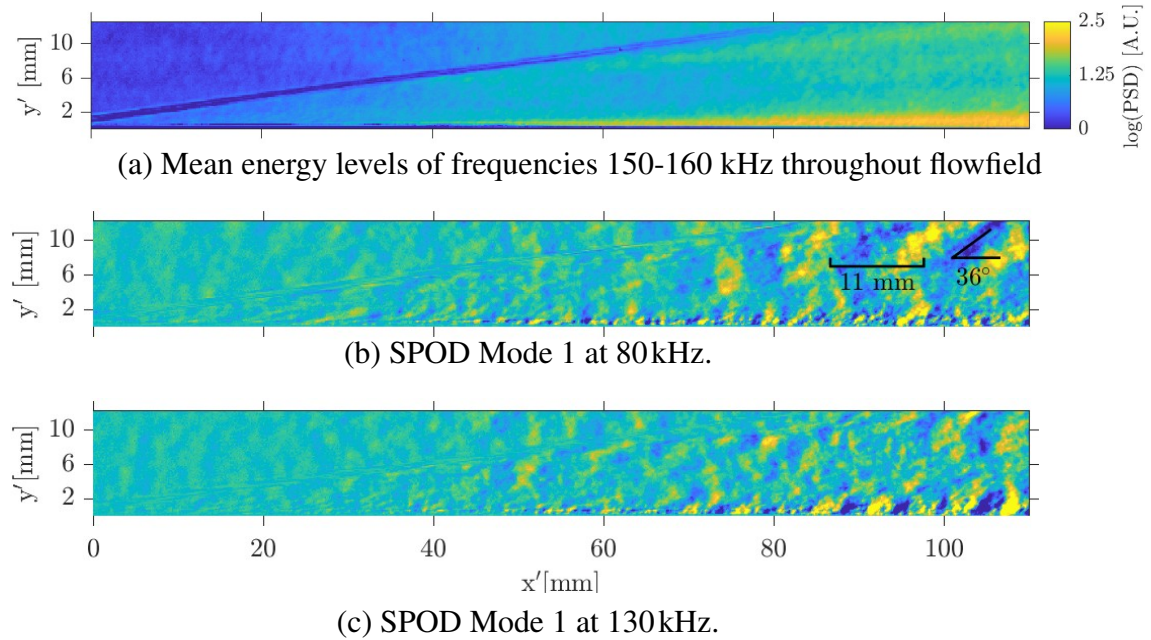


Figure 4.16: Summation of PSD energies (a) and SPOD Mode 1 shapes at 80kHz (b) and 130kHz (c) (Condition A; SPOD color scale is arbitrary).

We can attempt to identify whether the observed high-frequency unsteadiness is a result of organized flow structures by examining the modal energies captured by spectral proper orthogonal decomposition (SPOD). SPOD can be summarized as a decomposition of the data into a set of orthogonal modes and a solution of the corresponding eigenvalue problems, allowing the evolution of flow structures in space and time to be analyzed [61]. The SPOD spectrum for this condition (15° fin, condition A) showed elevated energy levels of the most energetic mode at approximately 80kHz and 130kHz. The flow structures that correspond to these frequencies are shown in Fig. 4.16b and 4.16c. We see in Fig. 4.16b that the structures causing the increase in amplitude at 80kHz are occurring behind the in-

viscid shock from around $x' = 80$ mm. Although these structures are relatively weak, they are nevertheless coherent with a wavelength of roughly 11 mm and they form at an angle of $\sim 36^\circ$ relative to the freestream. For the 130 kHz mode, shown in Fig. 4.16c, the increase in energy is almost exclusively within the boundary layer on the surface of the fin, and the relevant structures show little coherence. The SWBLI does not appear to create any notable coherent structures within the flat-plate boundary layer at 130 kHz, but there is a general enhancement of content at this frequency across the interaction which would be consistent with the onset of turbulence from approximately $x' = 50$ mm. An examination of the full range of frequencies in the strongest mode showed little other evidence of coherent structures within the flat-plate flowfield.

4.6 Comparison with canonical flow features

Considering these plan-view heat flux and schlieren results, the next step is to attempt to match the features seen with the canonical flow features expected for this geometry. Again, Alvi et al. [5] states that the strength of the interaction is governed by M_n and the flow structures change with the strength of the interaction. Taking the 15° case, for which the heat-flux features are most prominent, we have $M_n = 2.35$. Although there is no precedent in the literature that describes these flow features for a transitional boundary layer, if we use the turbulent case as a qualitative reference, the flow structures should fall between Fig. A.1e and Fig. A.1f. Using this description of the flowfield, we presume that the main peak is caused by the jet impinging upon the plate surface along the line of primary flow reattachment [5]. Similarly, the trough in the heat-flux distribution most likely occurs under the separation bubble. The cause of the secondary peak is less clear. It is possible that, since secondary separation is expected for an interaction of this strength, the secondary peak may be caused by secondary reattachment. This conjecture is supported by the fact

that the location of the secondary peak is consistent with our expectations for secondary reattachment. Furthermore, if secondary separation and reattachment is the cause of the secondary peak in heat flux, this would explain why this peak does not appear in the 5° case, since secondary separation is not expected at that interaction strength (i.e. $M_n = 1.38 < 1.5$).

An estimate for the location of the line of upstream influence in the turbulent case has been provided by Settles and Lu [14]. Using $(\beta_{UI} - \beta) = \arctan(c_1 M_\infty \sin \beta)$ and $c_1 \simeq 0.09$ yields a value of $\beta_{UI} = 34.4^\circ$. We note that the line of upstream influence is the one major flow feature identifiable in both TSP and schlieren: we have obtained values of $\beta_{UI} = 32.4^\circ$ from the TSP variance and $\beta_{UI} \approx 33^\circ$ from the circular arc schlieren PSD, both within 6% of the value provided by the empirical correlation. One final interesting aspect of the data collected is that the shape of the distributions in Fig. 4.12d, 4.12f, and 4.12h are qualitatively very similar to skin friction coefficient measurements recorded throughout the literature [5, 20, 32, 43], indicating at least a qualitative correspondence between the skin-friction and heat-flux distributions. Although it has been shown for a strong shock-wave/turbulent boundary-layer interaction that Reynolds analogy can be a tenuous assumption [42], this similarity suggests that it may have some validity in the present case, at least in a qualitative sense.

4.7 Summary

An experimental campaign investigating the flow behavior over a fin at incidence on a flat plate at Mach 6 was performed with a range of diagnostic techniques. Time-resolved temperature-sensitive paint results provided heat-flux distributions on sub-millisecond timescales. Quasi-conical symmetry of several heat-flux features was seen not only for their locations within the flowfield but also in their magnitudes. These measurements facilitated the iden-

tification of flow features such as reattachment lines, the end of the inception region, and the line of upstream influence. From these features, an estimate of a VCO location was able to be made, and the present data shows it to be noncoincident with the VCO determined by other measurement techniques. Moreover, these TSP results demonstrate that it is possible to reach sub-millisecond time-resolution on a model of this size in a low-enthalpy facility.

High-speed plan-view schlieren gave a new qualitative perspective of the flowfield and provided information on the spectral energies of the boundary layer as it progresses through the interaction. The foremost result from this analysis was an estimation of the line of upstream influence which agreed with both the TSP results and empirical predictions from the literature. Additionally, it was shown that there is no high-frequency content of a specific frequency dominating the interaction; this was corroborated by a SPOD analysis of the mode energies. SPOD mode shapes also showed that, although no frequency-specific activity dominates the entirety of the interaction, there is activity over a range of frequencies each affecting particular regions of the flowfield. Specifically, the SWBLI appear to promote a broadband energy elevation of the flow between the shock wave and the fin surface.

Chapter 5: Turbulent Case

The investigation into the fin-induced SWBLI with a turbulent incoming boundary layer consisted of a total of 56 tests. All fin angles (2.5° , 5° , 7.5° , 10° , 12.5° , and 15°) as well as the no-fin case were investigated at the four tunnel conditions listed in Table 2.3 with both the TSP and schlieren configurations. Because the increase in charge tube pressure, p_{Tube} , directly corresponds to an increase in unit Reynolds number, both of these terms will be used synonymously in referring to the different tunnel conditions in the subsequent discussion.

5.1 Undisturbed boundary layer

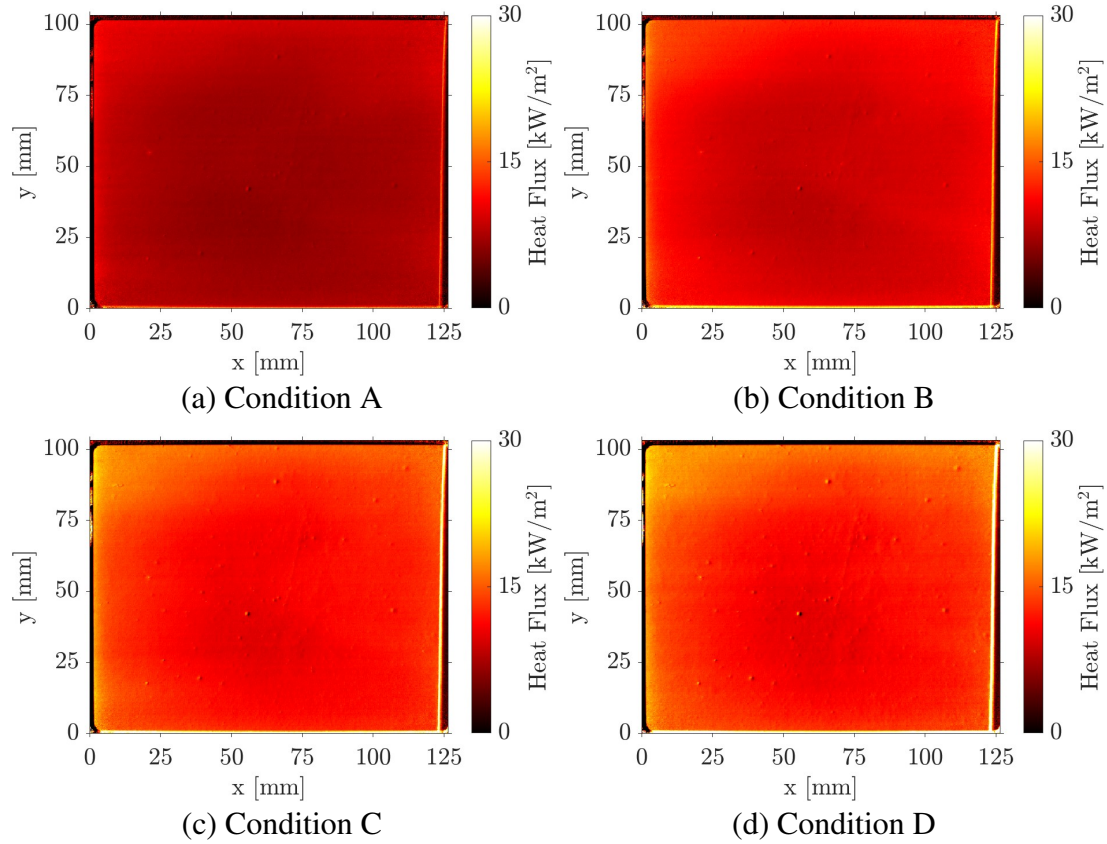


Figure 5.1: Mean heat-flux distribution for each condition.

To assess the state of the incoming boundary layer and to see the effect of varying the unit Reynolds number via the charge-tube pressure, time-averaged heat-flux distributions for the flat plate without the fin are presented in Fig. 5.1. From these heat-flux distributions, it can be seen that the amplitude of the heat flux remains relatively constant over the entirety of the region of interest. Additionally, it can be seen that these amplitudes increase with Reynolds number. Note that near the edges of the insert there are several regions measuring anomalously high amplitudes, in particular for where $x = 0 - 50\text{mm}$ and $y > 80\text{mm}$. It is most likely that these features are the result of the mounting method

or possibly a small step between the insert and the plate. At $x = 120$ mm there is also a sharp spike in the heat flux over the entire range of y -values, which is an artifact of the painting process. The trailing edge of the insert ($x = 120 - 125$ mm) was not painted so that a discrete step between the painted and unpainted areas was available to make an accurate measure of the paint thickness; this step manifests itself as the spike seen in Fig. 5.1. Since these anomalous features are common to all TSP measurements gathered on the HTLT test article, it is assumed that they are non-physical and the analyses contained herein will omit data gathered near the leading and trailing edges of the insert.

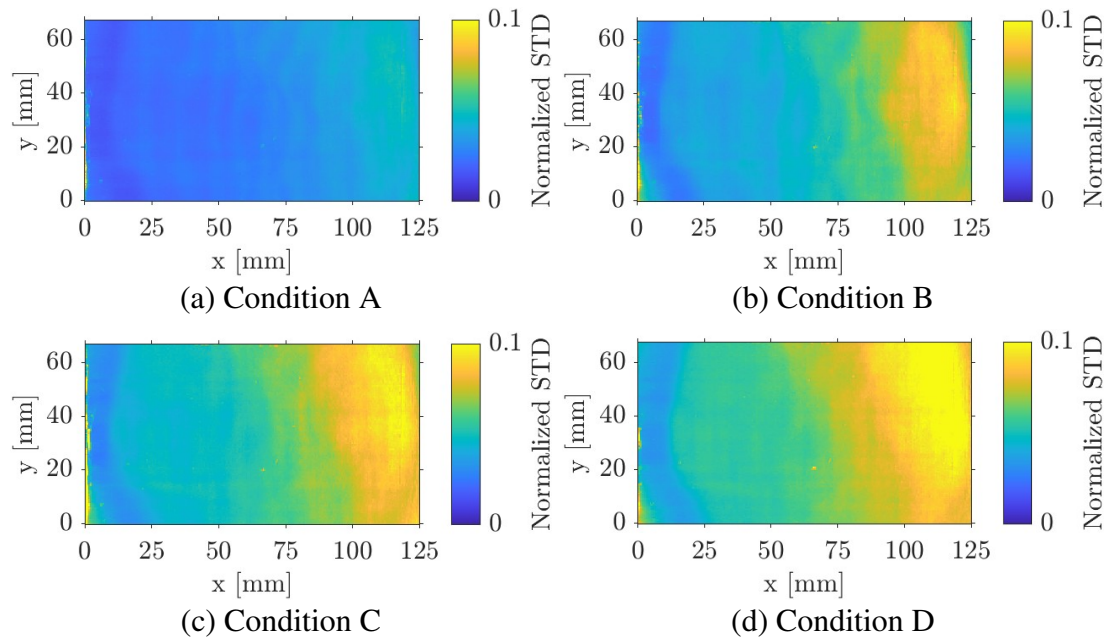


Figure 5.2: Normalized STD distribution for each condition.

A normalized schlieren STD analysis of each tunnel condition with no fin attached is shown in Fig. 5.2. From this we see a similar trend to that visible in the mean heat-flux analysis, in that the increase in Reynolds number results in an increase in the normalized STD. This indicates that, as the Reynolds number is increased, there is a higher level of variation in the boundary layer, particularly further downstream. In this case, however, there is also a clear gradient in the streamwise direction. Although the mean heat-flux

results in Fig. 5.1 and spanwise schlieren in Fig. 2.7 suggest a mature turbulent boundary layer, this streamwise gradient may indicate that the incoming boundary layer has still not reached a fully developed turbulent state as it passes over the region of interest. Again, anomalous behavior can be seen near the leading edge of the insert, particularly for $x < 5$ mm. As with the heat-flux distributions, data gathered from near the edges of the windows will be omitted in subsequent analyses.

Because of the qualitative similarity at the different test conditions, the following discussion will mainly consider the 50 bar case (condition D), as this condition typically resulted in the best signal-to-noise ratio. The tunnel condition for a given analysis will be indicated in the legend and/or caption of the figure. For results at other tunnel conditions, a comprehensive series of plots is given in Appendix D.

5.2 Time-averaged behavior

5.2.1 General observations

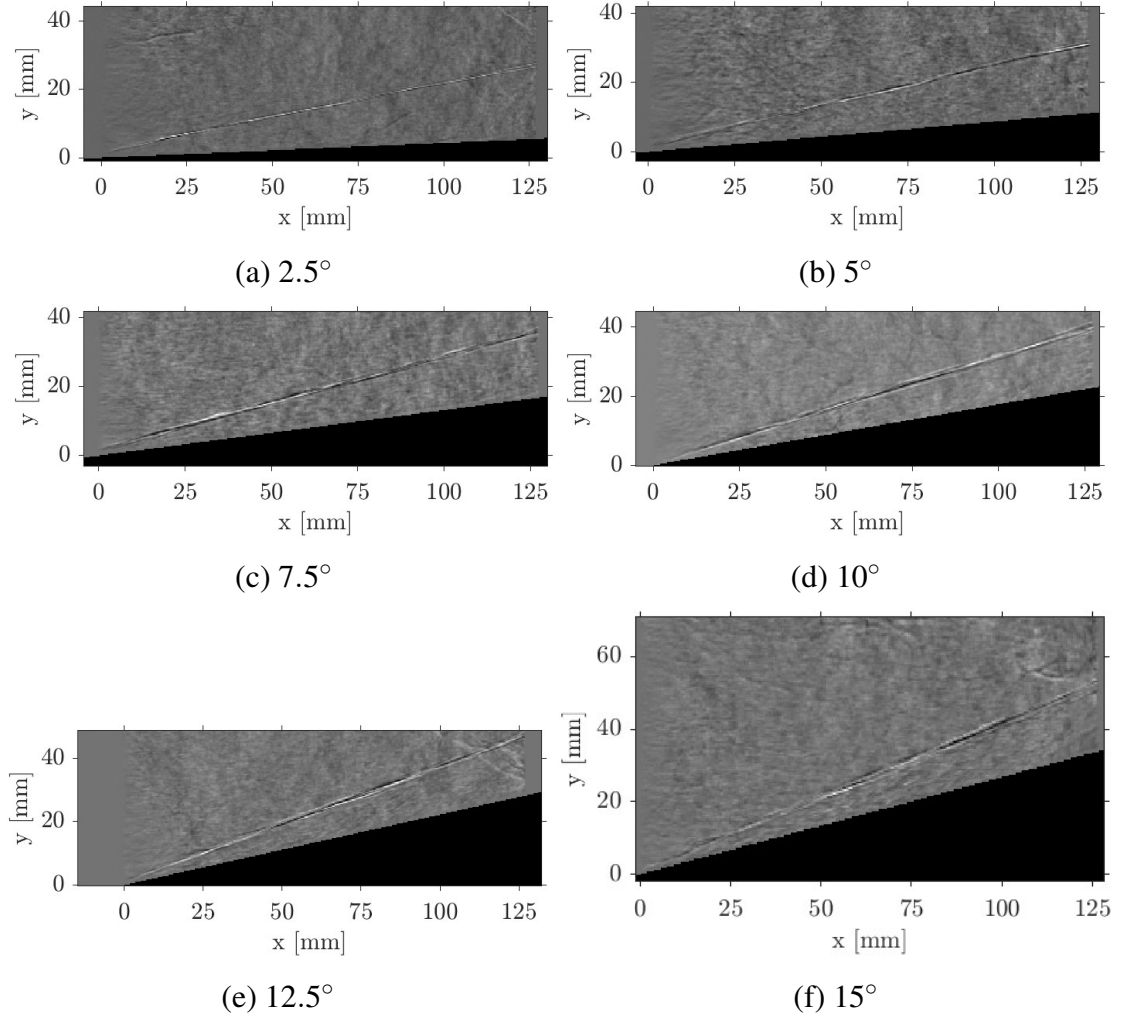


Figure 5.3: Reference-subtracted schlieren for each angle of attack (condition D).

As in the transitional case, the characteristic flow features of this SWBLI can be picked out from the reference-subtracted schlieren images presented in Fig. 5.3. Specifically, the inviscid shock wave and the boundary layer which develops on the surface of the fin are again visible. Although analysis of the transitional case suggested that the area between

the shock wave and the fin surface may contain features that are not seen outside the shock, there is no clear evidence of similar behavior from the reference-subtracted schlieren images for the turbulent case here. The relative uniformity of this flowfield could be expected: since the boundary layer is already turbulent as it passes through the field of view, one would not necessarily expect substantial changes to the boundary layer within this region. This contrasts with the transitional incoming boundary layer discussed in Ch. 4 where the boundary layer was transitioning and non-uniform flow features were anticipated.

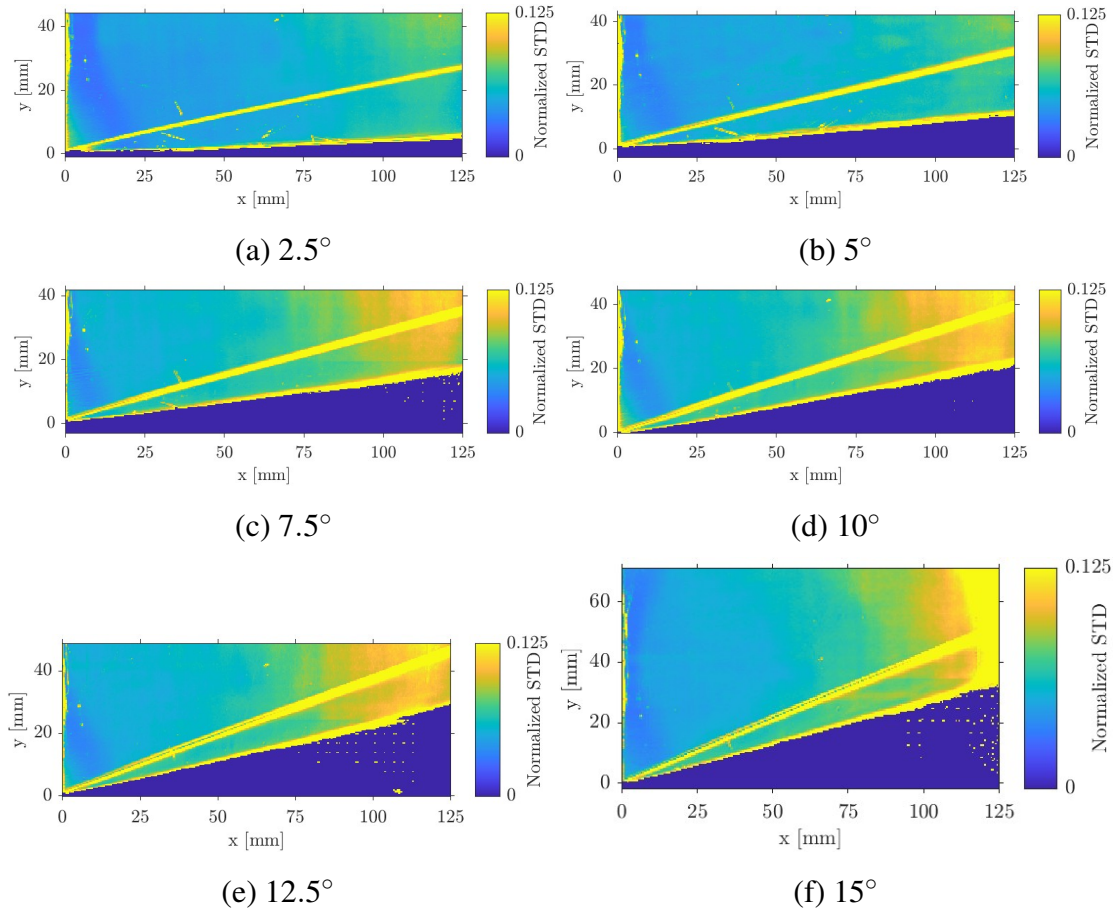


Figure 5.4: Normalized schlieren standard deviation for each angle of attack (condition D).

The normalized standard deviation (STD) over the steady test time for each angle of attack is plotted in Fig. 5.4. Comparing between the different interaction strengths, several

key features can be noted. As in the transitional case, the most prominent feature of these STD distributions is the elevated amplitudes between the shock wave and the fin surface. Progressing through the angles of attack, it is also clear that the magnitude of the difference across the shock increases with the strength of the interaction. At 2.5° and 5° , the STD values on either side of the shock are nearly identical, but for the 12.5° and 15° cases, there is a clear amplification across this boundary. Another feature of these STD distributions is that the streamwise gradients which were seen in the no-fin case (Fig. 5.2) are also present here both inboard and outboard of the shock wave. Specifically, comparing with Fig. 5.2d, which shows a noticeable increase in the STD amplitude between $x = 50 - 75$ mm, we can clearly see this same feature outside the shock for the 7.5° , 10° , 12.5° , and 15° cases. Inboard of the shock wave, this streamwise gradient is also present; however, it appears to be more gradual and also less clear due to the already-elevated STD amplitudes in this region. A notable contrast between current turbulent case and the transitional case is the STD amplitude near the inception region. In the transitional case, all three angles of attack displayed low amplitudes in the inception region. Figure 5.4 shows that, especially at larger angles of attack, the inception region contains higher amplitudes in the region where $x < 35$ mm. This result agrees with the preconceptions of the inception region as one where higher levels of unsteadiness are to be expected. Finally, these STD mappings show that for all fin angles, there are high STD amplitudes within the boundary layer on the surface of the fin. This elevation may be greater or have a further outboard extent for the larger angles of attack; however, due to the limited resolution of the plots in Fig. 5.4, this speculation is tenuous.

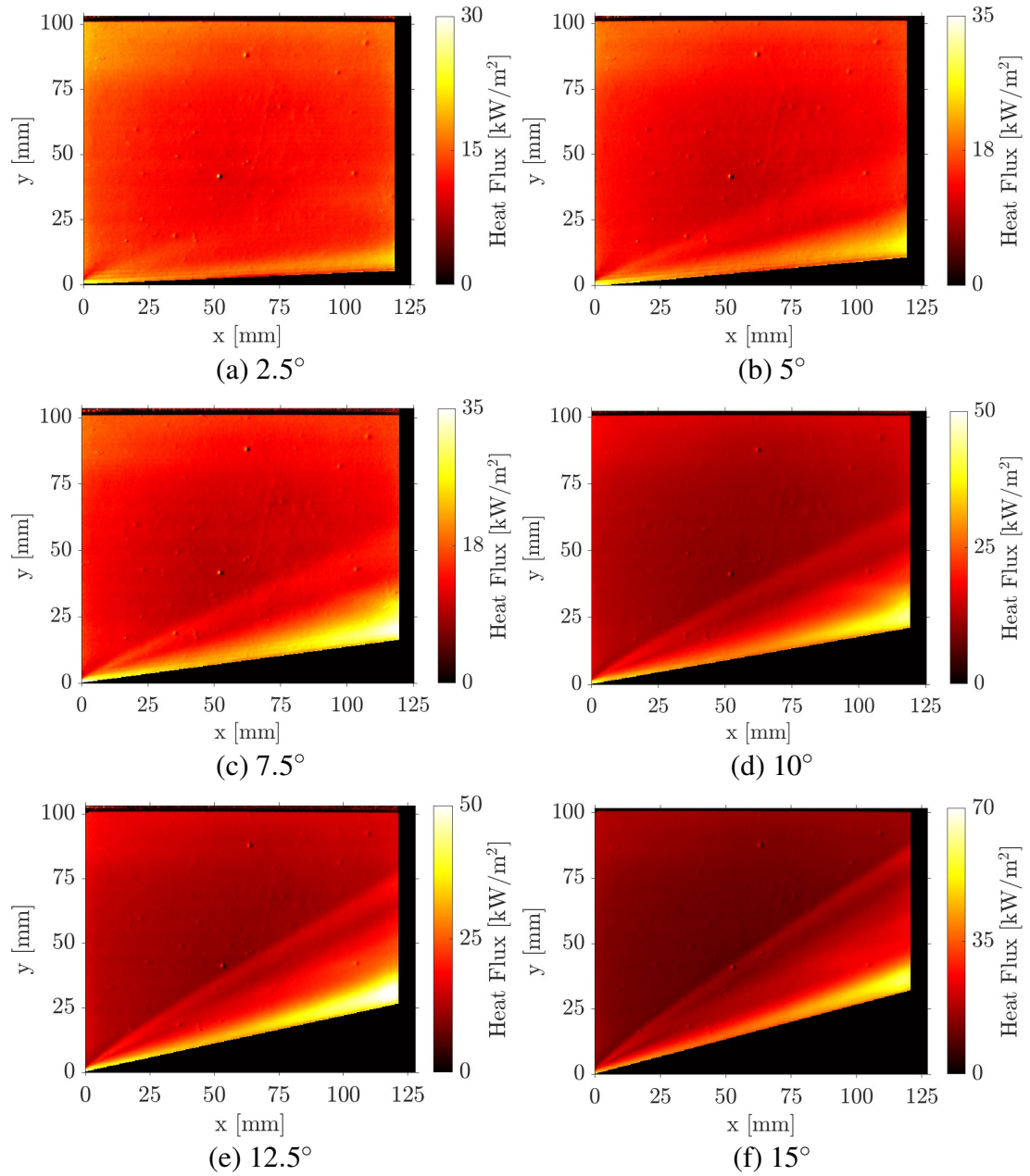


Figure 5.5: Mean heat-flux distribution for each angle of attack (condition D).

Figure 5.5 shows the mean heat-flux distribution for each angle of attack over the steady test time. In the 2.5° case, one can see the presence of a primary peak directly adjacent to the fin, but no substantial evidence of a secondary peak. For the 5° case, a clear primary peak, trough, and secondary peak become visible; this is a notable result when comparing

with the transitional case for which the 5° case did not display a secondary peak. Additionally, one can see the line of upstream influence outboard of the secondary peak. Moving to the 7.5° case, the peak-trough-peak distribution becomes more pronounced, but also begins to show differences compared to the heat-flux distributions of the transitional cases. Particularly, the decrease from the primary peak to the trough is more spread out; this will become more apparent when viewed in the conical coordinate system in §5.2.2. No significant differences arise as the angle of attack is increased from 7.5° to 10° . At 12.5° , there are indications of a bifurcation of the trough in that, close to the inception region, $x = 5 - 30$ mm, one can see a trough feature forming that lies at a different azimuthal angle to the main trough. Moving to the 15° case, this behavior becomes clearer as the secondary trough feature now lies directly adjacent to the primary peak, whereas the original trough lies adjacent to the line of upstream influence. Because of this split trough, a tertiary peak also arises between the two troughs. Hereafter, these troughs will be referred to as the primary and secondary trough with the secondary trough lying directly adjacent to the primary peak and the primary trough lying further outboard next to the line of upstream influence. This nomenclature is meant to reflect the onset of these features as M_n increases rather than their azimuthal locations as θ' is increased. Finally, looking at all angles of attack (and excluding the far downstream region of $x > 110$ mm due to the possibility of corruption previously discussed), one can see that the highest heat-flux amplitude for a given interaction occurs ubiquitously within the inception region; an important result since q_{Max} is likely a relevant design parameter.

5.2.2 Quasi-conical symmetry

Since quasi-conical symmetry is known to be present in the flow features of such fin-induced turbulent SWBLIs and was shown to also exist in the heat-flux distributions of the

transitional SWBLIs in Ch. 4, it is natural to anticipate its presence in the turbulent heat-flux distribution. However, due to the different characteristic features that have been found in the present heat-flux distribution, a slightly modified VCO search methodology is needed and is depicted in Fig. 5.6. As in the transitional case, a series of circular arcs are generated about the leading edge of the fin (gray in Fig. 5.6a). On the portions of this arc directly adjacent to the fin, the mean heat flux was extracted and the peak along each arc was found (purple asterisks). Further outboard, a threshold was set and, moving outboard to inboard, when this threshold was reached, the corresponding location was selected as a point on the line of upstream influence (green asterisks). Removing outliers and computing a linear regression through each of these groupings, a primary-peak line and a line of upstream influence were determined. As in the transitional case, the shaded regions in Fig. 5.6a show the standard error for prediction. Since it is known that, for the turbulent SWBLI, the inviscid shock wave also obeys the quasi-conical symmetry of the interaction, this is also plotted (cyan) in Fig. 5.6 as $\beta \pm 1^\circ$, where β is calculated from oblique-shock relations using the freestream conditions.

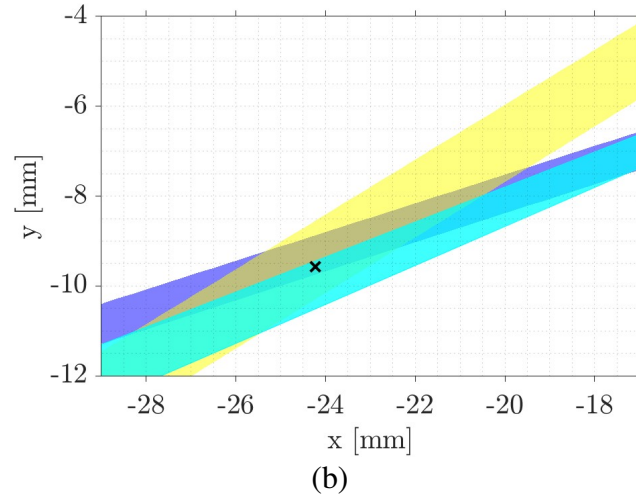
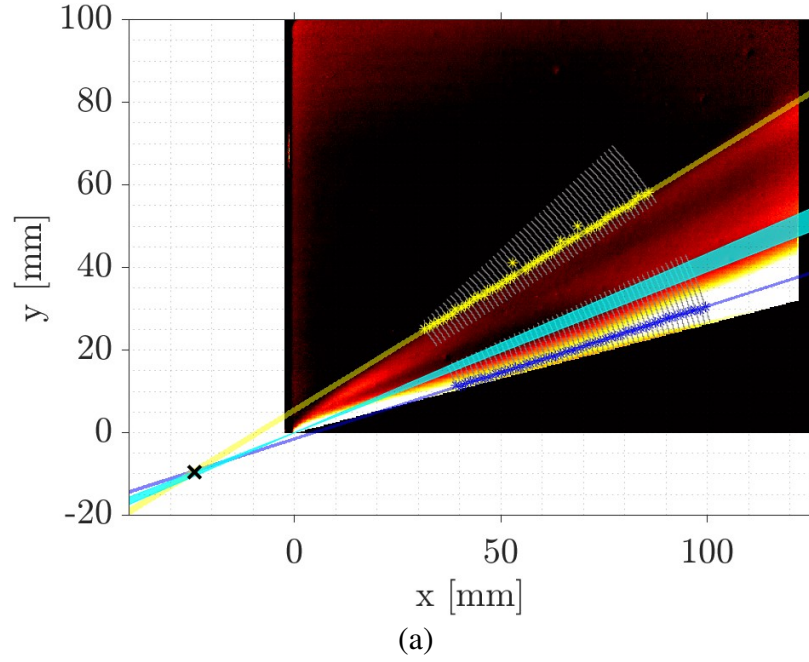


Figure 5.6: (a) VCO search methodology visualization and (b) region of possible VCO locations. $\times$ marks the determined VCO location.

Following both regressions and the extension of the shock wave upstream to their intersection points, we find that there is a region of overlap for all three shaded areas (Fig. 5.6b). This overlapping area is effectively a region of potential virtual conical origins locations. Because the three lines do not intersect at an individual point, a least-squares approach was used to find the best intersection point of the three lines ($\times$) and this was selected as the

VCO. Although this process can be applied iteratively in hopes of finding successively better estimates of a VCO location by using the previously determined location as a starting point (as opposed to the fin leading edge), iteration showed no progressive improvement in identifying the VCO and therefore was not used.

Because of the less prominent features, and particularly the inability to identify the line of upstream influence, VCOs were not able to be reliably determined for the 2.5° case. Therefore, this case is not included in parts of subsequent analyses. When it is included, the VCO used was determined subjectively to be a good approximate location. Further discussion on the VCO locations and trends as angle of attack and Reynolds number change is given later in §5.2.3.

Before considering these heat-flux distributions within the conical coordinate system, it is important to verify that the region under consideration is sufficiently far downstream to be in the self-similar region and not the inception region. To this end, the same analysis of the inception region as was performed for the transitional case in Ch. 4 is applied to the present data. The result of this process is shown for each fin angle in Fig. 5.7. From these plots, it can be seen that the inception region for the interaction ends at roughly 25 mm for the 2.5° case, 30 mm for the 5° case, and approximately 40 mm for all other cases. Because the VCO lies a certain distance upstream of the fin leading edge and varies from case to case, it is important to note that the value along the x -axis at which the data begins is not common among the different cases. Treating the first value on the x -axis as the location of the fin leading edge, these radial values can be adjusted to show the end of the inception region relative to the location of the fin leading edge. These results are summarized in Table 5.1.

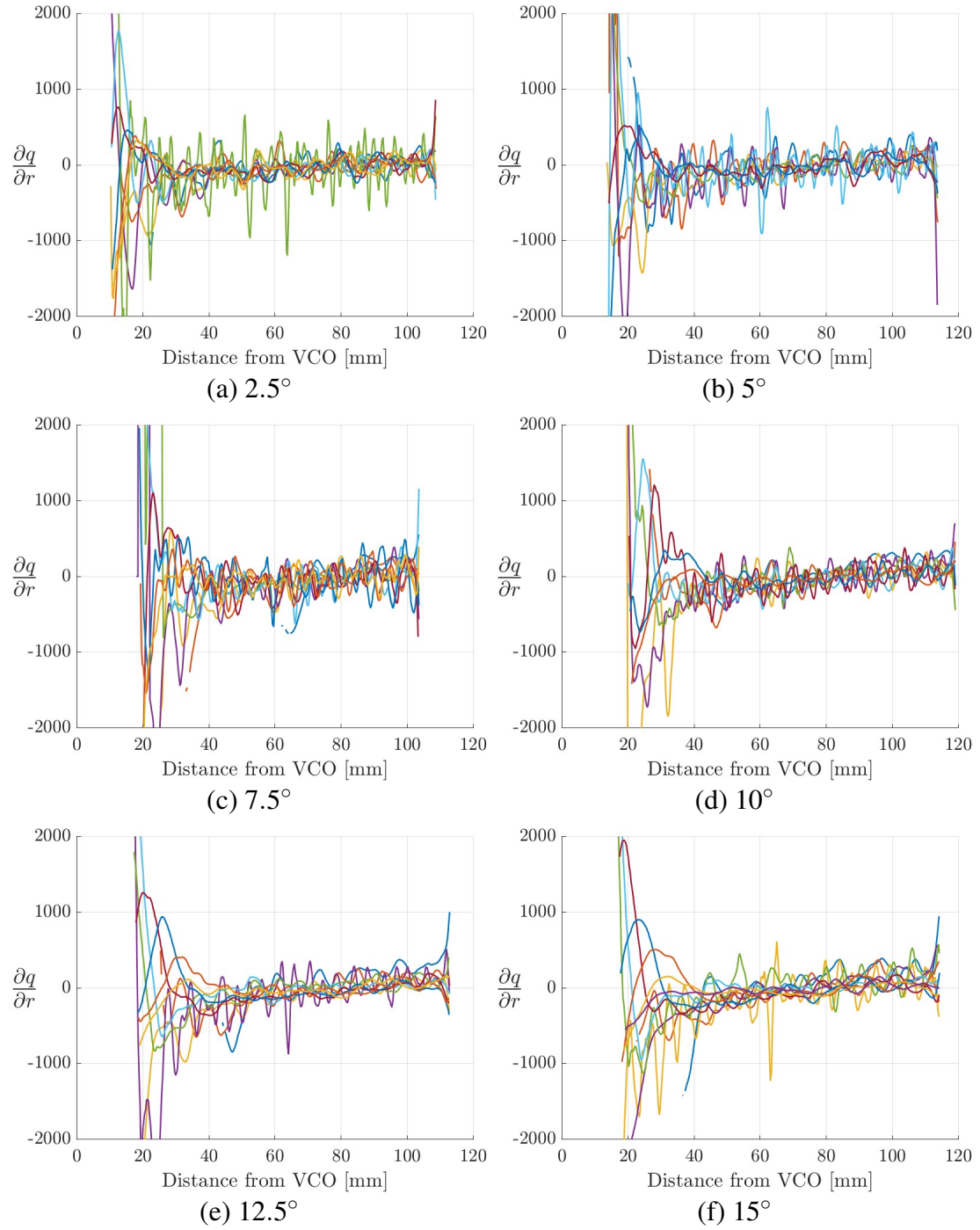


Figure 5.7: Radial derivatives of heat-flux distributions along rays originating at VCO (Condition D).

Case	2.5°	5°	7.5°	10°	12.5°	15°
Distance from VCO [mm]	25	30	40	40	40	40
Distance from leading edge [mm]	15	15	20	20	20	20

Table 5.1: Approximate distance between end of inception region and VCO/fin leading edge (condition D).

The consistency and narrow range of these values is an unexpected result as previous studies, such as that by Lu and Settles [33], have seen evidence that the inception length decreases as the interaction strength (i.e. fin angle) increases. It is possible that this consistency reflects an approach to the asymptotic limit described by Lu and Settles; however, that study saw the limiting value to be arbitrarily close to zero, which would be in contrast to the present case. Due to the subjectivity of determining an end of the inception region from Fig. 5.7, some caution should be exercised when interpreting the values in Table 5.1. Nonetheless, looking at the curvature in the line of upstream influence near the fin leading edge for the stronger interaction strengths in Fig. 5.5, it is clear that these cases have a finite, non-zero inception length. Although precise quantification of these values is not possible with the present data, a relatively clear demarcation of the beginning of the farfield region at roughly $x = 50$ mm can be made and is used henceforth.

With the heat-flux distribution appropriately split into inception and farfield regions, an investigation into the conical symmetry of the farfield region can be made. In the same manner as the transitional case, a series of arc and rays were generated about the VCO and used to construct a grid in the farfield region. The mean heat flux along the arcs was extracted and is plotted against the normalized angle from the fin, θ' , in Fig. 5.8. Similarly, the mean heat flux along the rays is plotted against distance from the VCO in Fig. 5.9. The arcs and rays from which these heat-flux values were extracted are provided in Appendix B.

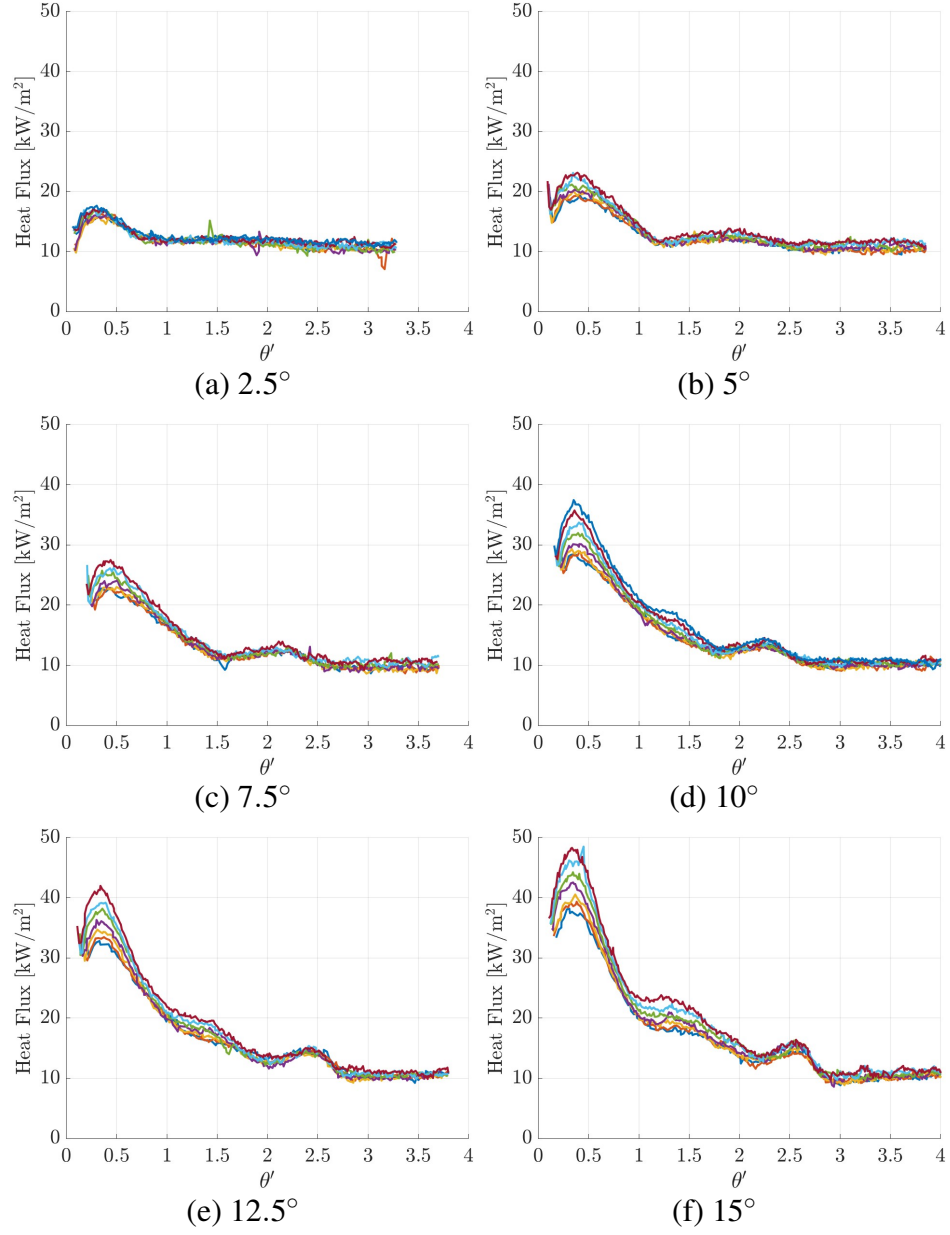


Figure 5.8: Heat-flux distribution along arcs centered about the VCO for each angle of attack (condition D).

From Figs. 5.8 and 5.9, it can be seen that all heat-flux distributions do show reasonable collapse when plotted along the arcs of this conical coordinate system and remain relatively constant when plotted along rays. This result verifies that the quasi-conical symmetry that has been shown for the canonical flow features of this turbulent SWBLI is also present in

its surface heat-flux distribution. Moreover, it provides further confidence in the methodology employed in locating the VCO. Aside from these conclusions, many attributes of this interaction which were suggested by Fig. 5.5 can be seen more definitively here.

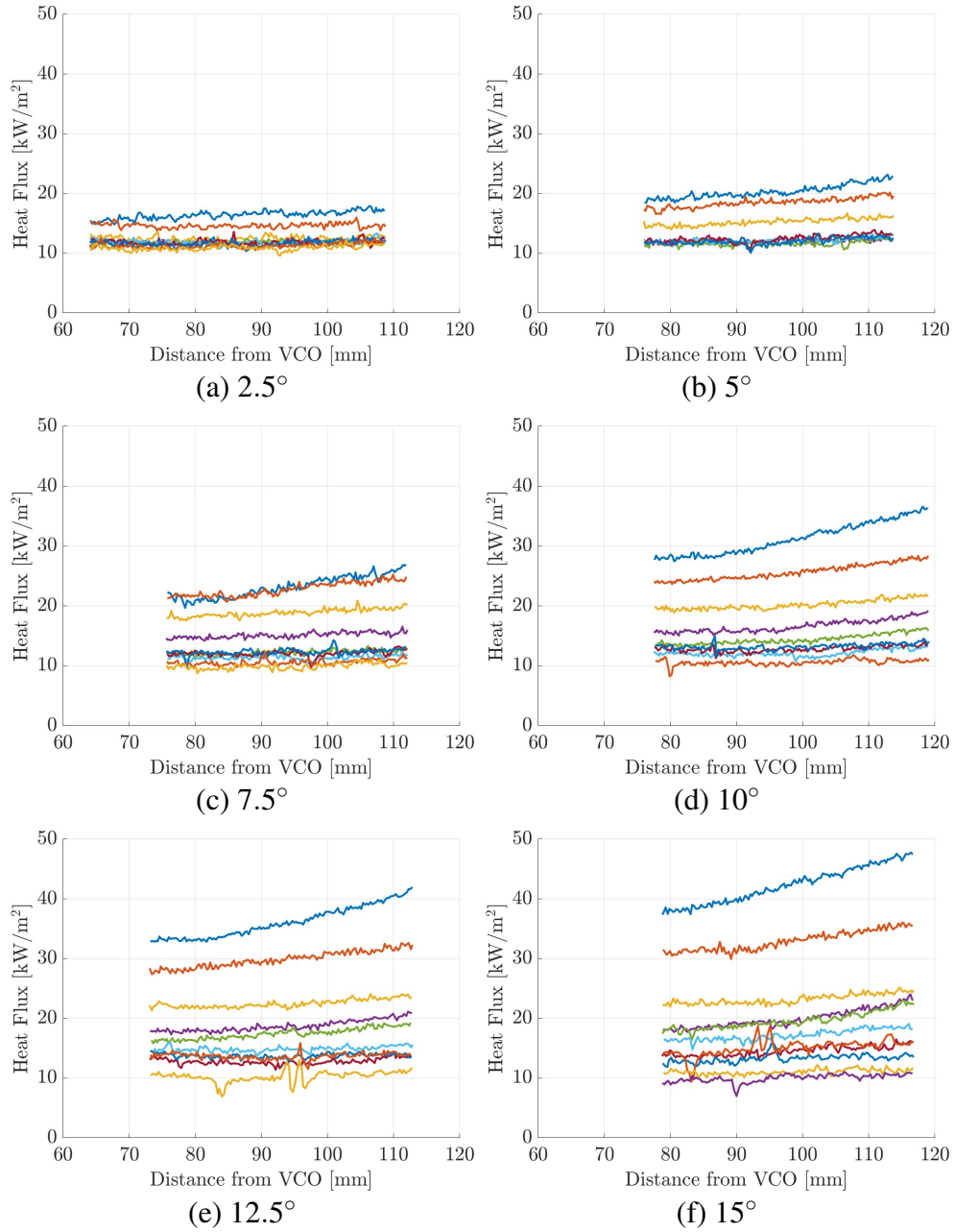


Figure 5.9: Heat-flux distribution along rays emanating from the VCO for each angle of attack (condition D).

First, the location of the primary peak for all angles of attack remains relatively constant at $\theta' = 0.4$ for all cases. This differs slightly from the transitional case analyzed in Ch. 4, where the location of the primary peak was found to be $\theta' = 0.28$ for the 5° case and $\theta' = 0.35$ for the 10° and 15° cases. Something that was not present in the transitional case or readily apparent in Fig. 5.5 is the range of maximum amplitudes that occur at the primary peak for a given case, the spread of which appears to grow with interaction strength. This is reflected in the range of maximum values seen at $\theta' = 0.4$ in the arc distributions, but it can also be seen in the positive gradients in the ray distributions. From the present data, it is difficult to say if this range of peak values is created by the SWBLI or is an effect of the possible corruption near the limits of the region of interest.

Moving through the development of the heat-flux distribution as the interaction strength increases, changes as the flowfield progresses through different flow regimes can be identified. In the 2.5° case, one can see that the primary peak is the solitary feature of this distribution with no evidence of a trough or secondary peak. Note that, at this combination of angle of attack and Mach number, $M_n = 1.18$. Referring again to the demarcations of flow regimes given by Alvi and Settles [5] in Fig. 1.5, primary separation begins when $M_n \gtrsim 1.2$. Therefore, it is not wholly surprising that the 2.5° case is unique in the features that are present, since it is the only case in which primary separation may not be occurring. The 5° case shows an increase in overall heating levels when compared to the 2.5° case and also gives the first indications of the formation of the primary trough at $\theta' = 1.25$ and the secondary peak at $\theta' \approx 2$. The 7.5° case is qualitatively very similar to the 5° case with a slight increase in magnitudes, but there is also a spreading out of the interaction. In this case, the primary trough is at $\theta' = 1.5$ and the secondary peak has moved marginally further outboard. Indeed, when comparing over all fin angles, this spreading seems to grow with interaction strength, with the final locations (i.e. when $\alpha = 15^\circ$) of the primary trough and secondary peak being at $\theta' \approx 2.2$ and $\theta' \approx 2.6$, respectively. In the 10° case,

the first indications of a bulge in the drop-off from the primary peak can be seen between $\theta' = 1 - 1.75$. This potentially signals the beginning of normal-shock formation that Alvi and Settles mark as starting at $M_n = 1.9$, as for $\alpha = 10^\circ$ and $M = 6.25$, $M_n = 1.85$. Interestingly, at 12.5° , the typical spreading of the interaction continues as expected, but it does not seem to include the bulge which remains roughly between $\theta' = 1 - 1.75$. Finally, for the 15° case, one can now see that this bulge has evolved into a secondary trough at $\theta' \approx 1.1$ and a tertiary peak at $\theta' \approx 1.3$. This evolution may correspond to beginning of supersonic reverse flow, which Alvi and Settles predict for $M_n > 2.1$, as $M_n = 2.11$ for $\alpha = 12.5^\circ$ and $M_n = 2.38$ for $\alpha = 15^\circ$. Again, even though the bulge has changed into a trough and peak, these features appear to have maintained their azimuthal position at roughly $\theta' = 1 - 1.75$.

As in the transitional case, the high-speed schlieren data can be used to obtain a power spectral density (PSD) estimate along analogous circular arcs. A PSD mapping for a circular arc 75 mm downstream of the fin leading edge is shown for each angle of attack in Fig. 5.10; the exact arc used can be found in Appendix B. One of the notable features in these mappings for the transitional case was the broadband drop-off at $\theta' \approx 2.5$ which was thought to show the line of upstream influence. From the mappings in Fig. 5.10, however, we see no clear evidence of a drop-off at any particular value of θ' . In fact, the only feature that appears for every case is the shock wave. Nevertheless, comparing between different interaction strengths, a few trends can be noted. First, it is clear that the amplitudes throughout the interaction are substantially lower for the 2.5° case compared to all of the other cases, suggesting lower levels of unsteadiness throughout the flowfield for this relatively weak interaction. Second, as the interaction strength is increased, there is an elevation in amplitudes along the entirety of the arc over all frequencies considered. Finally, as in the transitional case, one can see that for the strongest interactions, the highest power levels throughout the flowfield (excluding the shock wave itself) are confined to the region between the shock wave and the fin surface. Overall, these mappings show a relatively uni-

form and broadband interaction, which is to be anticipated when investigating a boundary layer that has already completed the transition process.

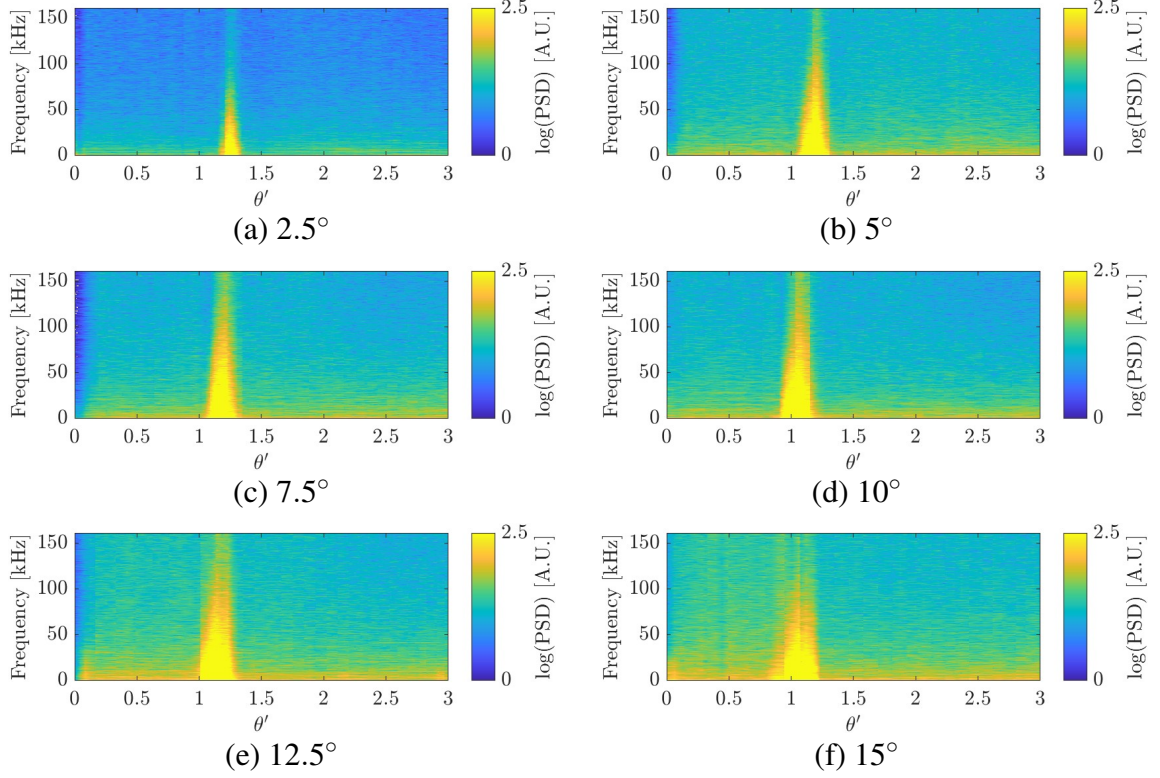


Figure 5.10: Power spectral density analysis along a circular arc for each angle of attack (condition D).

5.2.3 SWBLI variations throughout parameter space

For several of the characteristic features of the turbulent SWBLI, there are also significant changes in the amplitude and spatial location of these features as the Reynolds number (i.e. charge tube pressure of the HTLT facility) is varied. To avoid the overcrowding of legends in the plots of the subsequent discussion, the shape of the marker will be used to denote the fin angle and the marker/line coloring will denote the tunnel condition. This convention is summarized in Table 5.2. As mentioned previously, since key features were

not able to be reliably identified for the 2.5° interactions, this case is omitted from much of the subsequent discussion.

α	2.5°	5°	7.5°	10°	12.5°	15°
Marker	▼	◆	●	▲	■	★
Condition	A		B		C	
Color	Blue		Orange		Red	
					Yellow	

Table 5.2: Marker and color conventions.

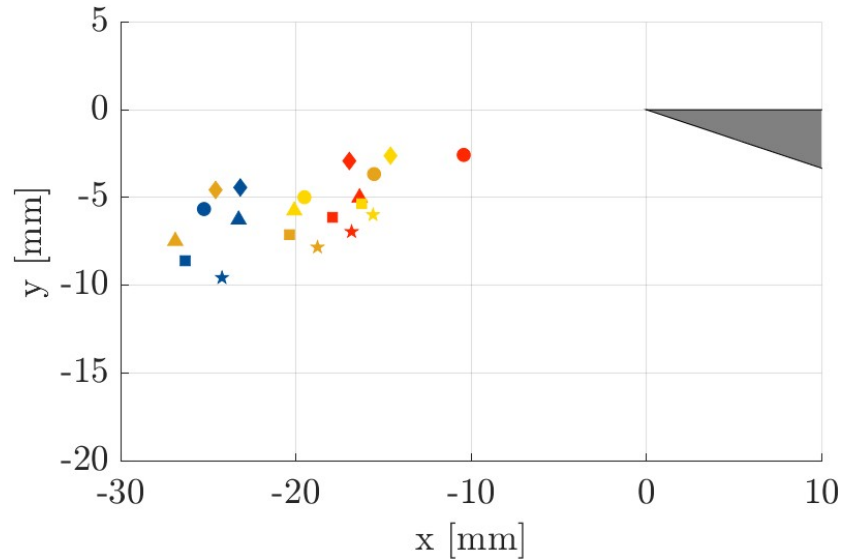


Figure 5.11: Scatterplot of virtual conical origin locations. Fin shown at $\alpha = 0^\circ$ for reference. See Table 5.2 for legend.

Figure 5.11 shows a scatterplot for all of the VCO locations that were able to be identified through the methodology described in §5.2.2. Looking first at the changes with angle of attack, it is clear that as the interaction strength increases, the line on which the VCOs lie falls further below the horizontal. To quantify this change, linear regressions were fitted through the VCOs for each fin angle and the slopes of these regression lines relative to the horizontal are: 11.78° , 12.17° , 12.90° , 17.44° , and 21.50° for $\alpha = 5^\circ$, 7.5° , 10° , 12.5° , and 15° , respectively. Because the shock-wave angle is one of the values that is typically

used to define the VCO location and β grows with α , this progression is to be anticipated.

Comparing these VCO locations across different tunnel conditions, one can see there is a tendency for the VCO to shift closer to the fin apex as the Reynolds number is increased. Particularly for the 12.5° and 15° cases, for which the signal-to-noise ratio was greatest and the VCO search methodology yielded the most confident results, there is a clear movement towards the leading edge as the Reynolds number is increased, with a very similar change to the VCO location for each case. This trend is more tenuous at lower angles of attack.

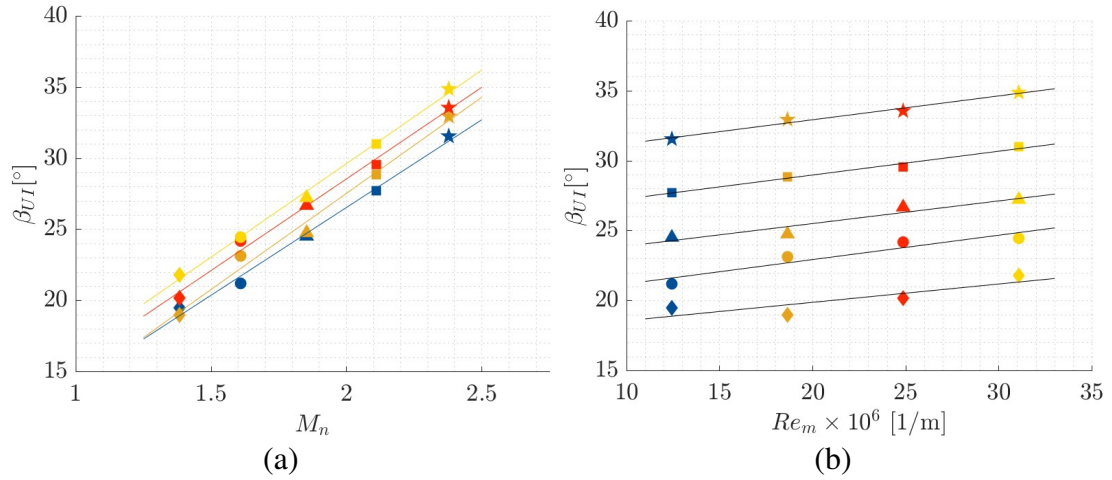


Figure 5.12: β_{UI} trends. See Table 5.2 for legend.

The location of the line of upstream influence also constitutes as an important parameter as this represents the farthest outboard extent of the interaction. Figure 5.12 shows the change in β_{UI} as M_n (i.e. interaction strength) and the Reynolds number are changed. First, considering the change as M_n is increased, there is a definite linear trend in the movement of β_{UI} , with a slight but constant offset between each of the regressions generated by the different tunnel conditions. As for the change as Reynolds number is increased, a similar linear pattern arises; however, the offset between the regressions is caused by the different angles of attack being considered. These two representations of the same behavior show that the location of β_{UI} is dependent both on the strength of the interaction

and on the freestream Reynolds number, but these effects seemingly influence the SWBLI independently in an additive manner.

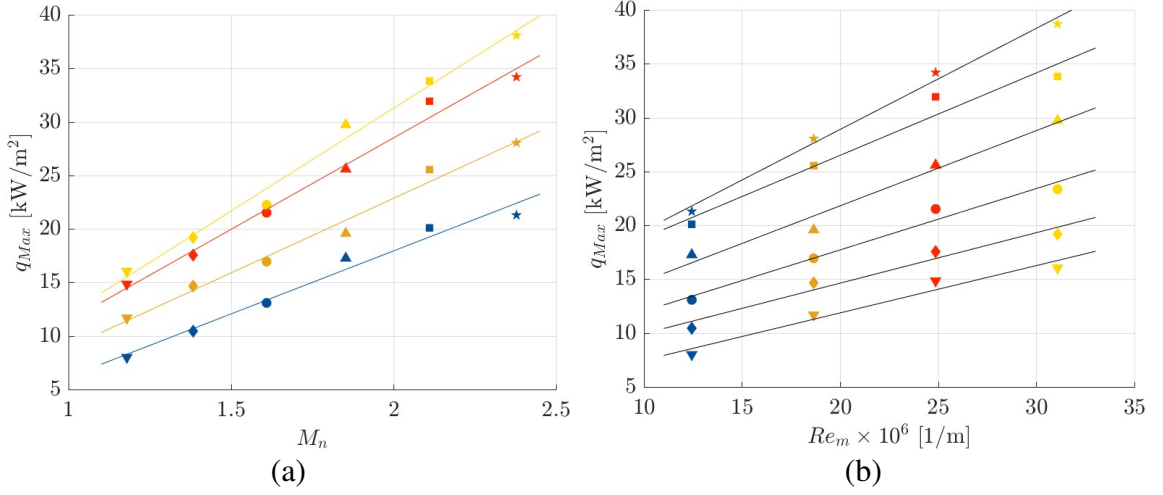


Figure 5.13: q_{max} amplitude trends. See Table 5.2 for legend.

As mentioned in §5.2.1, the amplitude and location of the maximum heat flux in the SWBLI are likely crucial parameters when considered in the context of hypersonic vehicle design. Although it was noted that the highest amplitude heat flux occurs within the inception region, this peak is relatively limited in terms of its spatial extent and is always just downstream of the fin leading edge. Because of the substantially larger spatial extent and comparable amplitude of the primary peak, this is also an important value to quantify throughout the parameter space. The amplitude of q_{Max} , which is defined as the average maximum along all arcs within the self-similar region when the mean heat flux is extracted, is plotted against M_n and Re_m in Fig. 5.13. As with the location of the line of upstream influence, it can be seen that the magnitude of q_{Max} also grows linearly as either M_n or Reynolds number is increased; however, in this case, the two quantities are related in a multiplicative manner as opposed to an additive one. The relatively constant offset seen in the value of β_{UI} in Fig. 5.12 is replaced here by an offset that grows as the interaction strength or Reynolds number is increased. Another important aspect of these data is

that the slope of the q_{Max} regression is greatest for the highest angle of attack and largest Reynolds number cases. This implies that for a vehicle in a high Reynolds number flow that will generate fin-induced SWBLI, the maximum surface heating can grow rapidly as the angle of attack of the shock-generator is increased, possibly imposing strict limitations on maximum deflection angles for a given fin-type control surface.

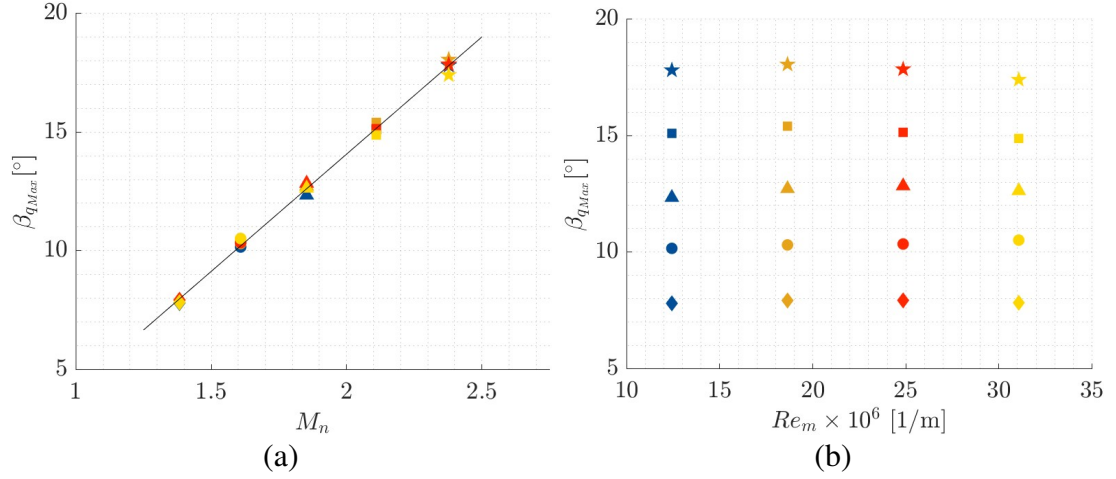


Figure 5.14: $\beta_{q_{Max}}$ trends. See Table 5.2 for legend.

The azimuthal location of the peak heating, $\beta_{q_{Max}}$, is shown plotted against M_n and charge tube pressure in Fig. 5.14. From this, we see that the angular location of the primary peak scales proportionally with the angle of attack, but there is virtually no dependency on the Reynolds number. Moreover, if, instead of $\beta_{q_{Max}}$, the quantity of $\beta_{q_{Max}} - \alpha$ is considered, it can be seen that this value remains nearly constant at $\beta_{q_{Max}} - \alpha \approx 2.75^\circ$ over the entirety of the parameter space.

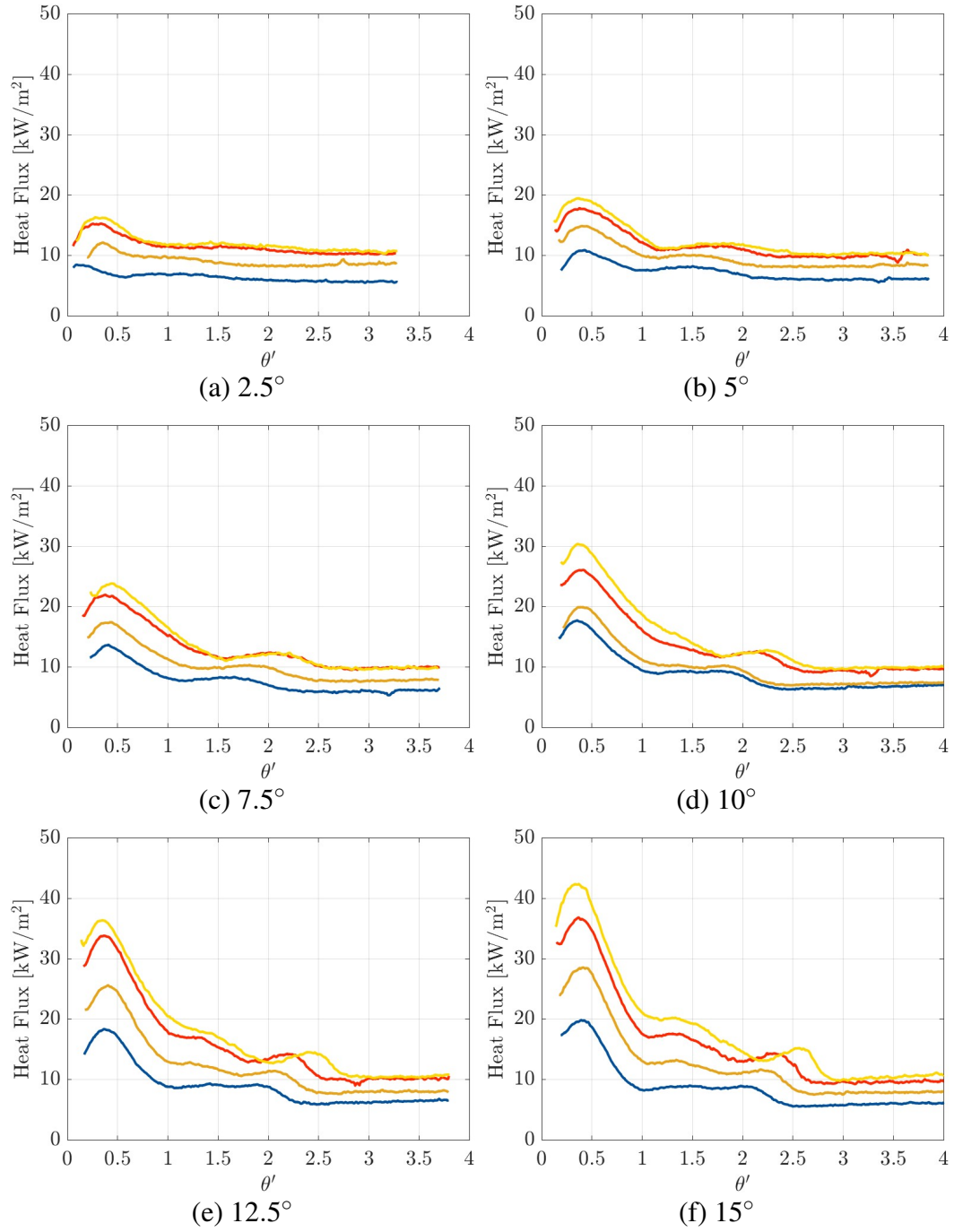


Figure 5.15: Heat-flux distribution along arcs and their variation with Reynolds number. See Table 5.2 for legend.

Since it was shown in Fig. 5.8 that the heat-flux distribution along a series of arcs centered about the VCO collapse in a quasi-conically symmetric manner, a mean of these distributions can be taken to create a single representative curve for a given case. We can then investigate how this characteristic curve for a given angle of attack changes as Reynolds number is varied, as in Fig. 5.15. Recalling from Fig. 5.8 that, as the angle of attack was increased, the interaction itself spreads out, we see that this is also true when the Reynolds number is increased but to a lesser extent. Taking the 10° case for example, one can see that the location of the primary trough is at $\theta' \approx 1.1$ for the 20bar case but shifts to $\theta' \approx 1.8$ for the 50bar case. As with the change induced by an increase in M_n , it appears that this spreading out affects the locations of the primary trough, secondary peak, and line of upstream influence (corroborating those results seen in Fig. 5.12b), whereas the locations of the primary peak, secondary trough, and tertiary peak seem to remain unaffected. Aside from changes to the azimuthal location of certain attributes, we see that the change in Reynolds number also causes a change to the relative amplitude of specific features; particularly the secondary trough and tertiary peak. Considering the 12.5° and 15° cases where these features first emerge, one can see that at the lowest charge tube pressure, there is no clear evidence of a secondary trough or tertiary peak. Rather, this region is better described as a plateau at the amplitude of the secondary peak. Yet, as the charge tube pressure is increased, the indications of the formation of the secondary trough and tertiary peak manifest themselves more clearly, and, at the 50 bar case, are prominent features. Finally, it is important to note that, although these characteristic distributions change substantially with both angle of attack and Reynolds number, all cases still exhibit quasi-conical symmetry and collapse when plotted about the VCO.

5.3 Unsteady SWBLI behavior

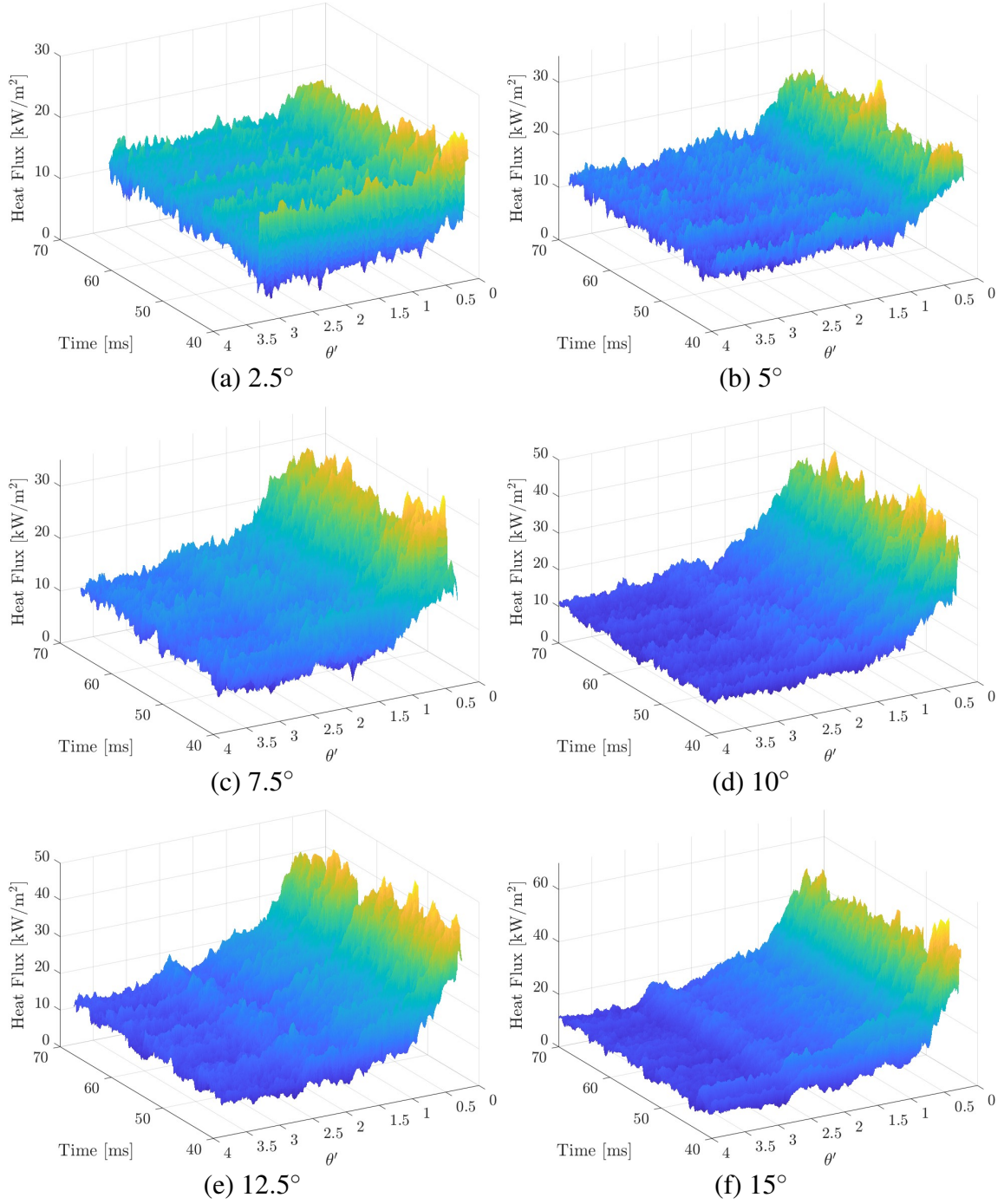


Figure 5.16: Heat-flux distribution versus azimuthal location vs time (condition D).

By considering a singular arc and tracking the heat-flux along it through time, an investigation can be made into the unsteady behavior of the surface heating. This is done for an arc in the middle of the farfield region for each angle of attack in Fig. 5.16 (specific arcs provided in Appendix B). Here it can be seen that the level of unsteadiness throughout the heat-flux distribution appears to vary proportionally with the mean heat flux at that location. That is, the level unsteadiness in the unaffected freestream ($\theta' > 3$) is relatively low; however, along the primary peak ($\theta' = 0.4$) where the mean heat flux is greatest, the unsteady fluctuations are of a much greater amplitude. Moreover, the unsteady behavior appears to be stochastic is natural with no apparent cyclic qualities (e.g., a periodic breathing behavior).

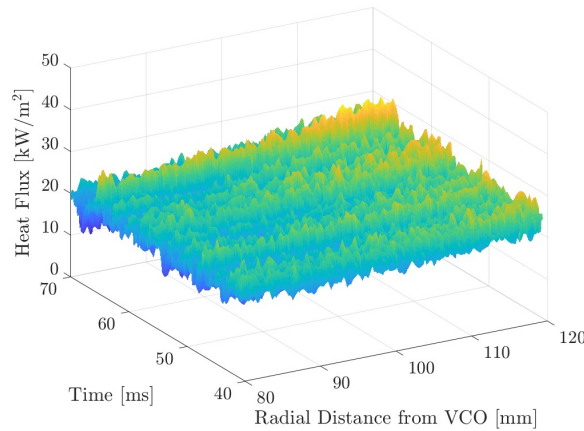


Figure 5.17: Heat-flux distribution versus radial distance from VCO versus time ($\alpha = 12.5^\circ$, condition B).

In the same manner, by looking along a given ray emanating from the VCO, the unsteady amplitudes and their variation with radial distance from the VCO can be analyzed. From the example case provided in Fig. 5.17, it can be seen that the unsteady amplitudes remain relatively constant with radial distance; this is qualitatively true over all angles of attack and Reynolds numbers. This consistency reflects the analogous behavior displayed by the mean heat flux along rays in the same region (Fig. 5.9), but, recalling the streamwise

gradients in STD amplitudes seen in Fig. 5.4, this largely constant level of unsteadiness is not necessarily to be expected.

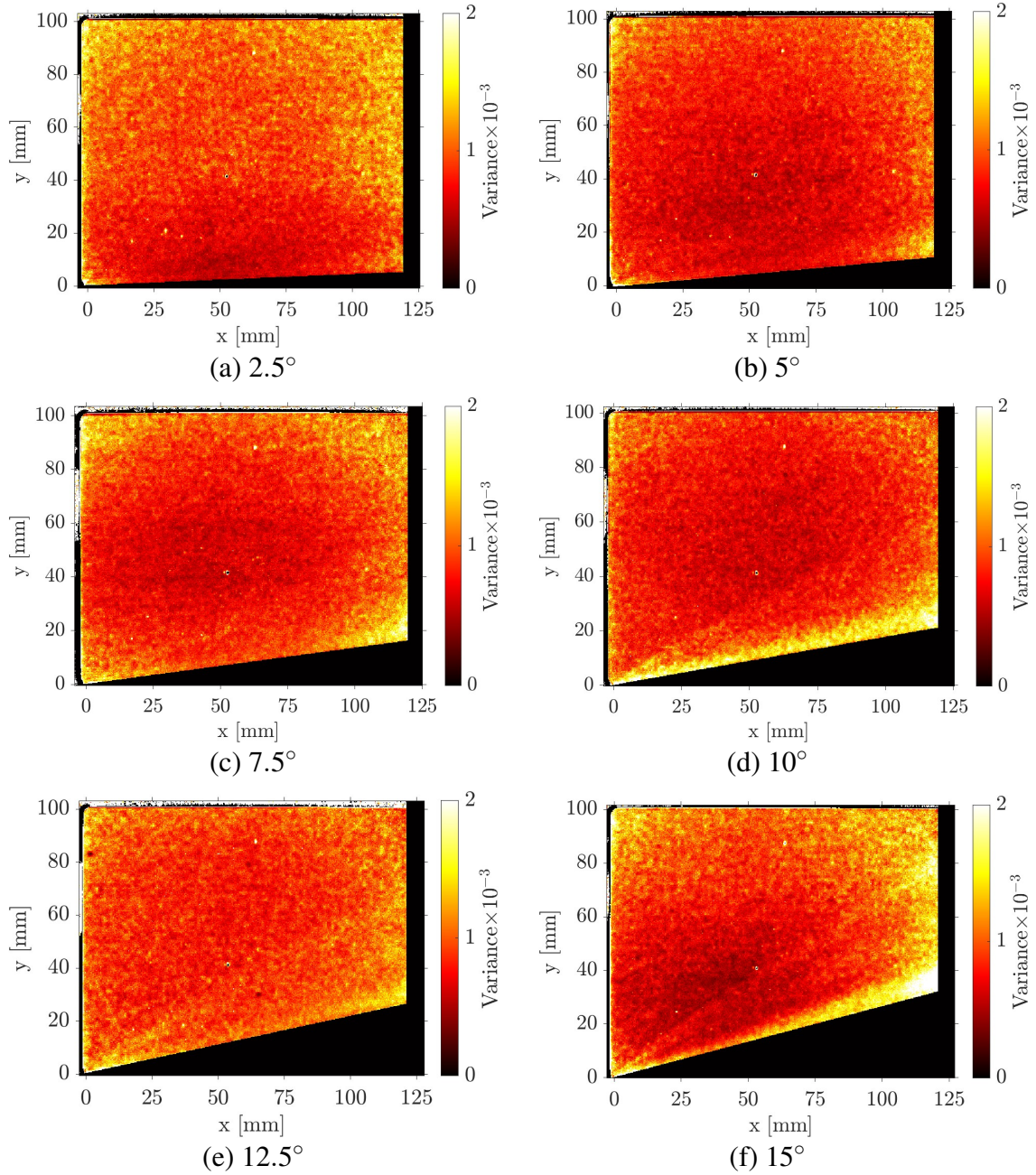


Figure 5.18: Variance normalized by mean heat flux (condition D).

The variance of the time-resolved heat flux normalized by the mean heat flux is shown for each angle of attack in Fig. 5.18. Looking at the weaker interactions where $\alpha = 2.5^\circ$ and $\alpha = 5^\circ$, there are no clearly discernible features in the area directly adjacent to the fin. This agrees with the postulation that the level of unsteadiness varies proportionally with the amplitude of the mean heat flux, as an increase in the variance, when normalized by the mean, would manifest as a uniform distribution with no distinct features. However, as the interaction strength is increased, one sees a distribution that qualitatively resembles the mean heat-flux distributions seen in Fig. 5.5. This implies that, at these interaction strengths, the variance of the time-resolved heat flux grows superlinearly with the mean heat flux. This is another significant result in terms of hypersonic vehicle design in that if a turbulent SWBLI with high surface heating is present, one would expect much higher levels of unsteadiness at this peak location than elsewhere throughout the interaction flowfield, possibly generating the maximum unsteady heating loads for this part of the vehicle by a large margin.

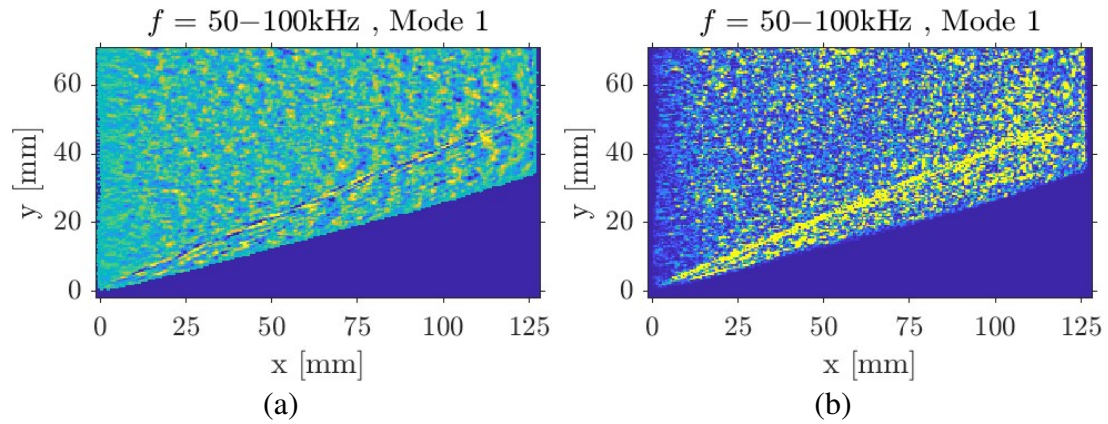


Figure 5.19: SPOD (a) mode visualization and (b) power distribution of the first mode for $f = 50 - 100\text{kHz}$ ($\alpha = 15^\circ$, Condition D).

The application of SPOD could help to inform us whether the unsteadiness of this turbulent SWBLI is being caused by any coherent flow structures. For example, at $\alpha = 15^\circ$

at Condition D as shown in Fig. 5.19a, it can be seen that, aside from the main shock wave, there are no distinct structures throughout the flowfield. Qualitatively, this is true over the entire parameter space investigated in that no coherent structures are present in the interaction at any combination of angle of attack and Reynolds number. However, by visualizing the SPOD mode energy distribution between 50 and 100 kHz as in Fig. 5.19b, one can once again see elevated energy levels in the region between the shock wave and the fin surface.

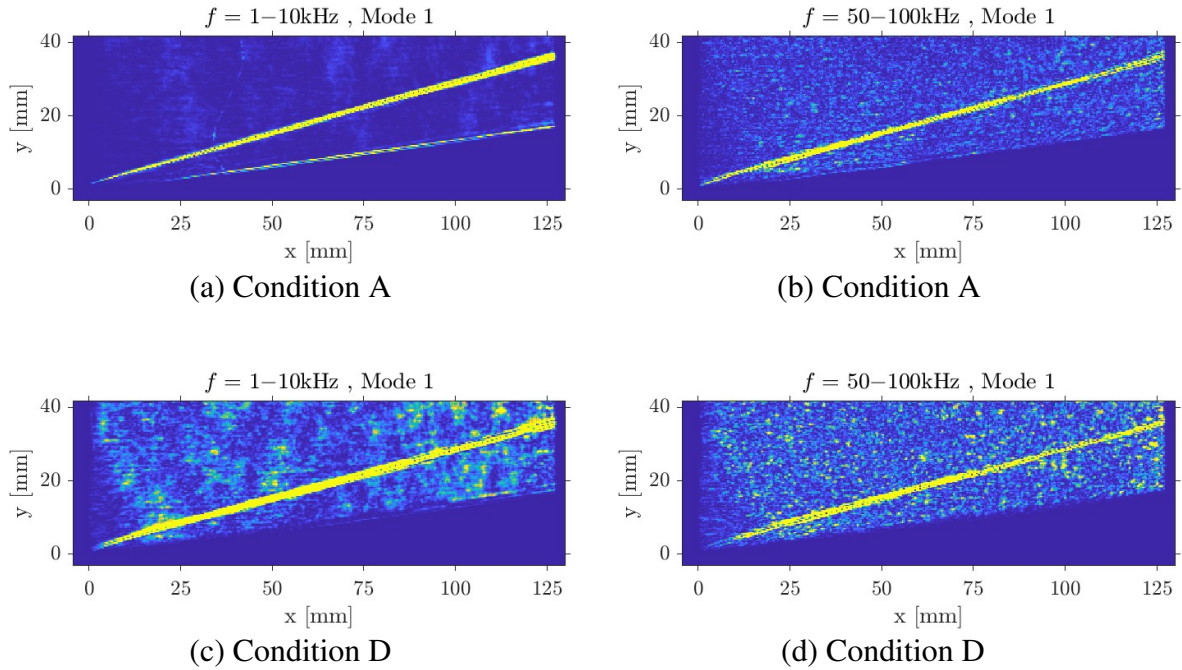


Figure 5.20: SPOD power distribution for $\alpha = 7.5^\circ$ at (a & b) condition A and (c & d) condition D for (a & c) low and (b & d) high frequency ranges.

Now looking at similar power distributions over two frequency ranges for fin angles of 7.5° and 15° at both condition A and D in Fig. 5.20 and Fig. 5.21, some notable behaviors can be observed. First, in the low frequency range (1 – 10 kHz), the energy contained within the fin boundary layer is higher for the low Reynolds number case as opposed to the high Reynolds number case. Additionally, the low frequency power distributions do not show a marked increase in energy between the shock wave and the fin as the angle of attack or

Reynolds number is increased. For the high frequency (50 – 100kHz) power distribution, a different behavior is seen. For both the 7.5° and 15° cases, there is no significant difference between the distributions at condition A and condition D; rather, there is a uniform rise in the amplitudes over the entire flowfield. Comparing between the 7.5° and 15° cases, the increase in fin angle once again generates increased amplitudes between the shock wave and the fin as was seen in the STD distributions of Fig. 5.4 and the PSD distributions of Fig. 5.10.

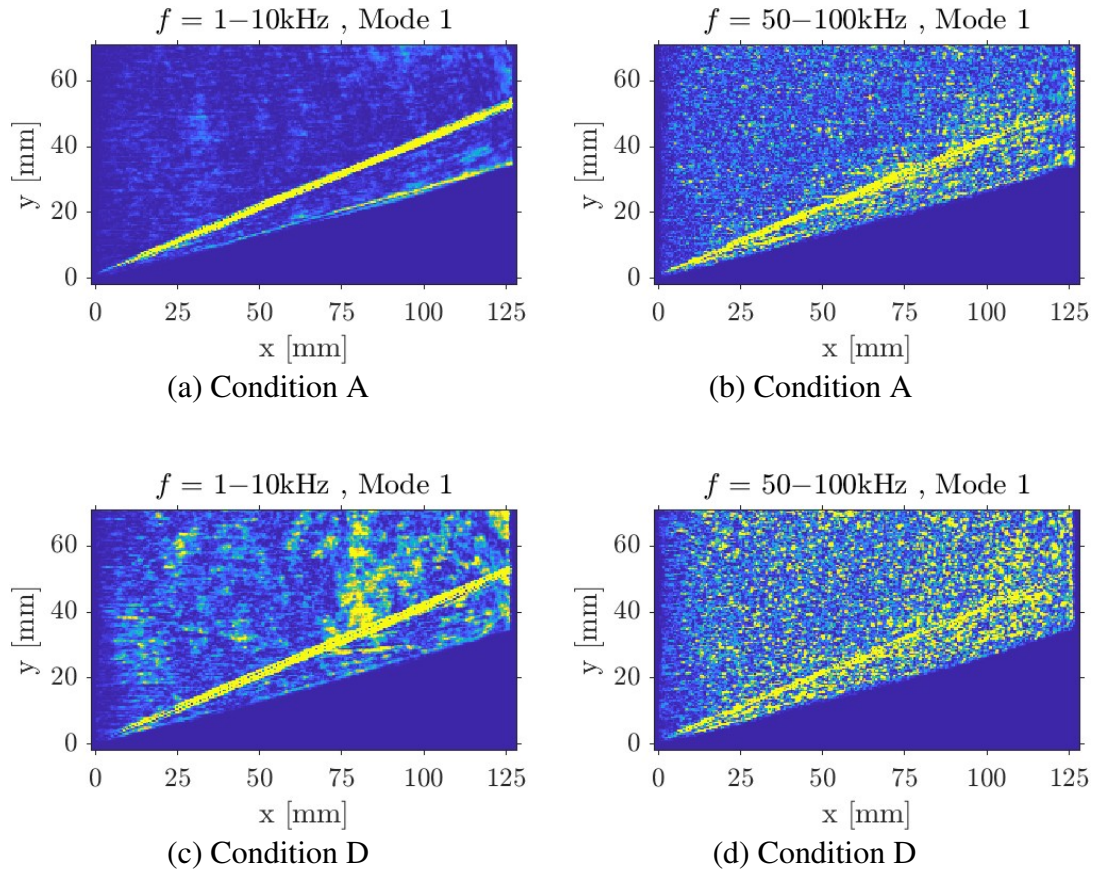


Figure 5.21: SPOD power distribution for $\alpha = 15^\circ$ at (a & b) condition A and (c & d) condition D for (a & c) low and (b & d) high frequency ranges.

5.4 Comparison with canonical flow features

α	2.5°	5°	7.5°	10°	12.5°	15°
M_n	1.18	1.38	1.61	1.85	2.11	2.38

Table 5.3: Normal component of Mach number for each angle of attack

Since the flowfield structures of turbulent SWBLI have been studied in depth throughout the literature, an attempt can be made to match the features from the heat-flux distribution and plan-view schlieren to those of the canonical flowfield. Because the normal component of the incoming Mach number will determine the extant flow structures of a given interaction, this value is present for each case in Table 5.3 for reference. The flow-field sketches of Fig. A.1 will be treated as the canonical features of the interaction.

In the heat-flux distributions along arcs presented in Fig. 5.8 and Fig. 5.15, the location of the primary peak of a given distribution remains relatively constant throughout the parameter space (as was shown in Fig. 5.14) at $\theta' = 0.4$. Assuming that this peak is caused by primary flow reattachment, nondimensionalizing the angular values of R_1 (denoted A_1) provided in Fig. A.1 yields θ' values ranging from roughly $0.45 - 0.52$. Despite these values being slightly larger than those observed in the current study, we note the constant presence of primary flow attachment in Fig. A.1 as well as the consistency in the primary peak location in the present heat-flux results. Therefore, it is reasonable to conjecture that the primary peak in the heat-flux distribution is caused by primary flow reattachment.

Because the location of secondary reattachment is not provided in the sketches of Fig. A.1, the location of secondary separation, S_2 , will be used as an approximation. Normalizing these angular values results in $\theta'_{S_2} \approx 1.1 - 1.4$. Comparing this range of values to those of Fig. 5.8, and recalling that secondary separation is only expected for $M_n > 1.5$,

it appears that the bulge that develops at the stronger interaction strengths is most likely caused by the onset and growth of the secondary separation bubble.

Moving further outboard to the locations of primary separation and the line of upstream influence, the relation between the heat-flux distribution and the flowfield features becomes less clear. When converted to the nondimensional form, the location of primary separation is $\theta'_{S_1} \approx 1.2 - 2$ and the location of the line of upstream influence is $\theta'_{UI} \approx 1.4 - 2.1$. It is possible that the primary trough of the heat-flux distributions corresponds the location of primary separation; however, this speculation is tenuous. As for the line of upstream influence, over all of the cases considered in this study, $\theta'_{UI} > 2$ and, for most, $\theta' \approx 2.5$. Again using $(\beta_{UI} - \beta) = \arctan(c_1 M_\infty \sin \beta)$ and $c_1 \simeq 0.09$ from Settles and Lu [14] results in $\theta'_{UI} \approx 1.72 - 2.64$ (for $\alpha = 2.5^\circ - 15^\circ$). This prediction agrees better with the results gathered from the heat-flux distributions but still seem to yield an under-prediction. Because the values from Alvi and Settles never reach values greater than $\theta' \approx 2.1$ and the consistent under-prediction from Settles and Lu's correlation, it seems plausible that these features as they are defined are not necessarily caused by the same flow phenomenon. In other words, the initial increase in heat flux relative to the unaffected freestream does not occur at the same location that the incoming boundary layer starts to be affected by the SWBLI.

Although the normal component of the Mach number examined in prior work and the present study are relatively consistent, the influence of Reynolds number, freestream Mach number, and other relevant parameters is not fully captured; therefore, some caution should be exercised when making comparisons between the present results and those of the literature.

5.5 Summary

A series of experiments were conducted to investigate the surface heating and flowfield development of a sharp-fin-induced turbulent SWBLI at Mach 6.25. Tests with fin angles of 2.5° , 5° , 7.5° , 10° , 12.5° , and 15° as well as a no-fin case were run at units Reynolds numbers of 12.4, 18.6, 24.9, and 31.1 million per meter in the University of Maryland's recently-commissioned high-temperature Ludwig tube facility.

Time-resolved temperature-sensitive paint measurements provided heat-flux measurements over the region of interest on sub-millisecond timescales and facilitated a study of the variation of the heat-flux distribution throughout the parameter space. From these results, it was seen that the mean heat-flux distribution obeys the quasi-conical symmetry that is observed by the other flow structures of this interaction. Moreover, it also demonstrated that these mean heat-flux features can be used to locate a virtual conical origin through which the inviscid shock wave also passes. The heat-flux distributions showed a relatively constant inception length regardless of the strength of the interaction. In the farfield region, the evolution of several distinct heat-flux features was seen. Particularly, the peak-trough-peak distribution which was seen in the transitional case and throughout the literature was shown to change into a distribution with a tertiary peak and a secondary trough at combinations of high Reynolds number and high angles of attack. It is possible that the presence of the tertiary peak in the heat-flux distribution is caused by secondary separation, as the azimuthal locations of these features appear to agree fairly well. Moving throughout the parameter space showed the location of the line of upstream influence to depend on both the strength of the interaction and the Reynolds number in an additive and independent manner. For the amplitude of the maximum heat flux measured throughout the interaction, there was also a dependency on both of these quantities; however, in this case, there appeared to be a multiplicative relationship between the interaction strength and Reynolds

number which is an important result in terms of vehicle design. The location of the maximum heat-flux peak was shown to remain nearly constant at $\alpha+2.75^\circ$. Considering the changes in the azimuthal heat-flux distribution as Reynolds number was increased showed a spreading out of the interaction as well as an increase in overall magnitudes, particularly at higher interaction strengths.

Considering the time-resolved behavior of the surface heating over the test time showed that the unsteadiness of the heat flux increased with the mean magnitude at that location, meaning the maximum unsteady heating loads occurring at the primary heat flux peak. This is an important conclusion as it raises the possibility that the unsteady heating seen at this location may be the largest seen throughout the interaction by a large margin. Additionally, an analysis of the variance of the heat flux showed it to grow proportionally with the mean heat flux at lower interaction strengths, whereas there was evidence of superlinear growth at higher interaction strengths.

High-speed plan-view schlieren imaging showed that there is significant elevation of energy levels in the region between the inviscid shock wave and fin surface. This elevated energy occurs over a broad range of frequencies with no dominance exhibited by a particular frequency band. This was corroborated by a power spectral density analysis of the high-speed schlieren along an azimuthal arc. A standard deviation analysis of the schlieren also showed that the difference in amplitude inboard and outboard of the shock wave increases with interaction strength. An SPOD analysis showed no evidence of coherent structures throughout the interaction. At low interaction strengths and lower Reynolds numbers, this analysis showed relatively high energy of low frequency content within the fin boundary layer. At high angles of attack and Reynolds numbers, non-coherent elevated energies levels were once again seen between the inviscid shock wave and fin surface.

Chapter 6: Conclusion

6.1 Summary

This study investigated the canonical flow problem of the sharp-fin-induced shock-wave/boundary-layer interaction at hypersonic Mach numbers. An experimental campaign in the University of Maryland's HyperTERP reflected-shock tunnel was conducted to study the case of such SWBLIs for a transitional incoming boundary layer at fin angles of 5° , 10° , and 15° as well as a no-fin case. This campaign also demonstrated the feasibility of fast-response high-sensitivity temperature-sensitive paint (TSP) on a large-scale test article and plan-view high-speed schlieren for the fin/flat-plate configuration. The TSP was demonstrated to be able to gather time-resolved heat-flux measurements on sub-millisecond timescales with an experimental error of $< 13\%$. From the analysis of this data, it was shown that the heat-flux distribution in the transitional case observed the same quasi-conical symmetry that has been seen for other flow features of this interaction in the laminar and turbulent cases. This was a significant result as this symmetry is not necessarily to be expected for an incoming boundary layer which is undergoing significant nonlinear development as it enters the SWBLI. Additionally, using the location of the primary and secondary peaks found within the heat-flux distributions, a virtual conical origin (VCO) could be determined; however, this location did not appear to coincide with the the VCO locations classically determined by other methods. Further analyses were performed to investigate the length of the inception region and the unsteady heating behavior

throughout the interaction flowfield. The unsteadiness of the heating appeared to be relatively uniform within the farfield region, whereas increased levels of unsteadiness were observed within the inception region. Quantitative results were also obtained through a signal-processing analysis of the plan-view high-speed schlieren data. Normalized standard deviations, power spectral density (PSD) estimates, and spectral proper orthogonal decomposition (SPOD) were employed; the primary conclusion reached via these techniques was that there is an elevation of energy in the region between the inviscid shock wave and the fin surface. Moreover, there was little evidence that any of these elevated energies were due to the existence of coherent structures.

Before this SWBLI could be studied for the case of a turbulent incoming boundary layer, the freestream flow characterization of the University of Maryland's high-temperature Ludwig tube facility was necessary. Through a Pitot rake survey, high-speed schlieren imaging, and Femtosecond Laser Electronic Excitation Tagging (FLEET) velocimetry, this wind tunnel was characterized at both Mach-8 and Mach-6.25 conditions. The Mach-8 flowfield was shown to have a core flow diameter of roughly ~ 300 ms with steady test times of 40 – 80 ms. The Mach-6.25 steady test times were on the order of ~ 100 ms with a core flow that is at least 184 mm in diameter. Both of the Pitot rake surveys were corroborated by FLEET velocimetry measurements and neither gave any evidence of a wake generated by the fast-acting piston system of the tunnel.

With this facility characterized, the fin-induced SWBLI was characterized for the case of an turbulent incoming boundary layer. Using the same diagnostics as were demonstrated in the HyperTERP campaign, this interaction was studied at four separate Reynolds numbers (12.4, 18.6, 24.9, and 31.1 million per meter) at angles of attack of 2.5°, 5°, 7.5°, 10°, 12.5°, and 15°, together with the no-fin case. An analysis of this data within the conical coordinate system showed that, like the other features of this turbulent SWBLI, the heat-flux distribution also follows an approximate quasi-conical symmetry. Using the an-

gular locations of the primary peak, the line of upstream influence, and an extension of the inviscid shock wave, a VCO location could be determined. Unlike the transitional case, the inviscid shock wave was reliably found to be a feature that passed through the VCO. Within this conical coordinate system, heat-flux distributions along circular arcs showed the peak-trough-peak distributions consistent with those seen in the literature. At higher interaction strengths, this distribution developed a tertiary peak and secondary trough at azimuthal locations that indicated these features to possibly result from secondary separation and reattachment. Along rays emanating from the VCO, a relatively constant heat flux was observed. Along these same rays, the inception length, as determined by the numerical gradient of the heat-flux distribution, proved to be relatively constant over a range of interaction strengths. A parametric study of the distributions showed a dependency of the location of the line of upstream influence and the maximum heat flux seen in the SWBLI on both the interaction strength and Reynolds number. For the location of the line of upstream influence, these factors appeared to act additively; however, for the maximum heat-flux amplitude, there seemed to be a multiplicative relationship. At all combinations of interaction strengths and Reynolds numbers, the location of maximum heating remained constant at $\alpha + 2.75^\circ$ where α is the fin angle. Furthermore, as the Reynolds number was increased, there was a notable spreading out of the interaction and the development of features such as the tertiary peak and secondary trough which were not seen at lower Reynolds numbers. An analysis of the unsteady heat-flux behavior showed that the unsteadiness in the instantaneous heat flux increases with the mean heat flux at that location. This resulted in the conclusion that the highest unsteady heat-flux fluctuations occur at the location of the highest mean heat flux and within the inception region. This results in the unsteady heating loads at the primary peak being even greater than the mean heating at that location would initially indicate. Plan-view high-speed schlieren showed similar results to what was seen in the transitional case in that there are elevated standard deviation and PSD amplitudes

in the region between the shock wave and the fin surface. This was seen throughout the parameter space but was definitively more prominent at higher interaction strengths. Once again the PSD and SPOD analyses showed that these elevated energy levels were generated over a broad band of frequencies. SPOD mode visualizations clearly showed that no coherent structures were present anywhere throughout the interaction. Nonetheless, the SPOD power distributions showed some indications of a dependency on both Reynolds number and interaction strength.

6.2 Contributions

This study has made contributions to the understanding of the fin-induced shock-wave/boundary-layer interactions at hypersonic conditions, the implementation of experimental techniques, and developing capabilities of hypersonic ground-testing at the University of Maryland. As for experimental techniques, the campaign within the HyperTERP facility was the first to demonstrate the efficacy of fast-response high-sensitivity TSP on a test article of this scale. Although this TSP formulation and methodology had been used previously, it was on a significantly smaller physical scale; the present work is much more indicative of the typical dimensions used for high-speed wind tunnel testing. Additionally, the extremely high temporal response of this TSP methodology should be emphasized: while mean heat-flux measurements are relatively common with TSP, time-resolved sub-millisecond heat-flux measurements are unprecedented at the present conditions. The other experimental approach that was shown to be capable of gathering useful quantitative data in the HyperTERP campaign was that of plan-view high-speed schlieren. As mentioned previously, most historic work on the fin/flat-plate geometry employed fin-aligned optical diagnostics. Although this approach is extremely useful in acquiring data in the plane orthogonal to the fin and plate, it provides no information on the streamwise development of

the flow. The present campaigns showed the merits of the plan-view approach: notably, that it is both feasible from a test-article-fabrication point of view and useful for investigating the streamwise development of the flowfield as it encounters the SWBLI.

In terms of hypersonic ground testing, the work completed in this study played a large part in the commissioning of the HTLT facility at the University of Maryland. The combination of physical scale, Mach number, and Reynolds number capability of this facility make it unique amongst tunnels at educational institutions. This range of capabilities is even more notable when considering the available diagnostic methods, short turnover time, and low per-run cost. Therefore, the commissioning and characterization of the HTLT facility is a significant contribution to the ground-testing capabilities in the hypersonic regime.

Most notably, a number of contributions were made to the understanding of the flow physics of the fin-induced shock-wave/boundary-layer interaction at hypersonic conditions. The foremost of these contribution was the elucidation of the global surface-heating distribution of such interactions for both transitional and turbulent conditions. Despite the handful of extant studies in the literature that had investigated fin-induced SWBLI heating, most were done at a substantially lower spatial resolution and with no temporal resolution. Aside from the utility of the measurements obtained throughout these campaigns as a purely quantitative metric, insight was gained as to how this surface heating behaved when considered with the canonical flow features of this SWBLI. In particular, it was shown that this heat-flux distribution obeys the same quasi-conical symmetry that is observed for other surface and flow features of this interaction. This was the first definitive demonstration of quasi-conical symmetry for the heat-flux distribution in the turbulent case and, it was the first evidence of the presence of any sort of symmetry for the transitional case. Another important contribution of this work was that of the unsteady heating behaviors throughout this interaction. Particularly, the finding that the largest unsteady heating loads in the turbulent case occur along the primary peak and within the inception region is a consequential take-

away when considering these results and their implications to hypersonic vehicle design. In this context, the variation of amplitudes and azimuthal locations of key variables in turbulent interactions as both the fin angle and Reynolds number change is another significant contribution. Finally, the excitation of relevant amplitudes as the flow enters the SWBLI, as shown by the plan-view schlieren, is a meaningful step in developing the understanding of the effects of this SWBLI as it processes the flat-plate boundary layer.

6.3 Future work

There are many ways in which the present work could be furthered. With a parameter space that has so many variable that can be manipulated, this presents many directions in which this work can be taken. The same study applied to swept fin, blunted fins, compliant geometries, and so on would all constitute valuable contributions to the understanding of this complex interaction. Excluding these alterations to the test article, modifications to the diagnostics and parameter space considered here may also prove valuable. Examples may include a larger field of view to encompass the effects of this interaction downstream of the fin, a more focused survey on fins at low angles of attack, or the application of TSP to the surface of the fin. A particularly interesting research question would be further elucidation of the relationship between the heat-flux distributions and the known canonical flow features. Although the present work give some early evidence that the evolution of the tertiary peak may be caused by the arrival of secondary reattachment, the same conclusions were not able to be reached for other features known to be present in the canonical interaction. The means of solving this problem may lie in a simultaneous TSP and fin-aligned optical diagnosis; however, this again brings up the limits of fin-aligned optics when trying to investigate fins at low angles of attack. The present study also motivates a more in-depth examination of the unsteady heating loads present within the inception region and along the

primary peak. With these shown to be the locations within the flowfield where the highest mean and unsteady heating loads are present, there is substantial reason to believe that this areas will present some of the most challenging hurdles when designing control surfaces for hypersonic aircraft.

Appendix A: Canonical flow features

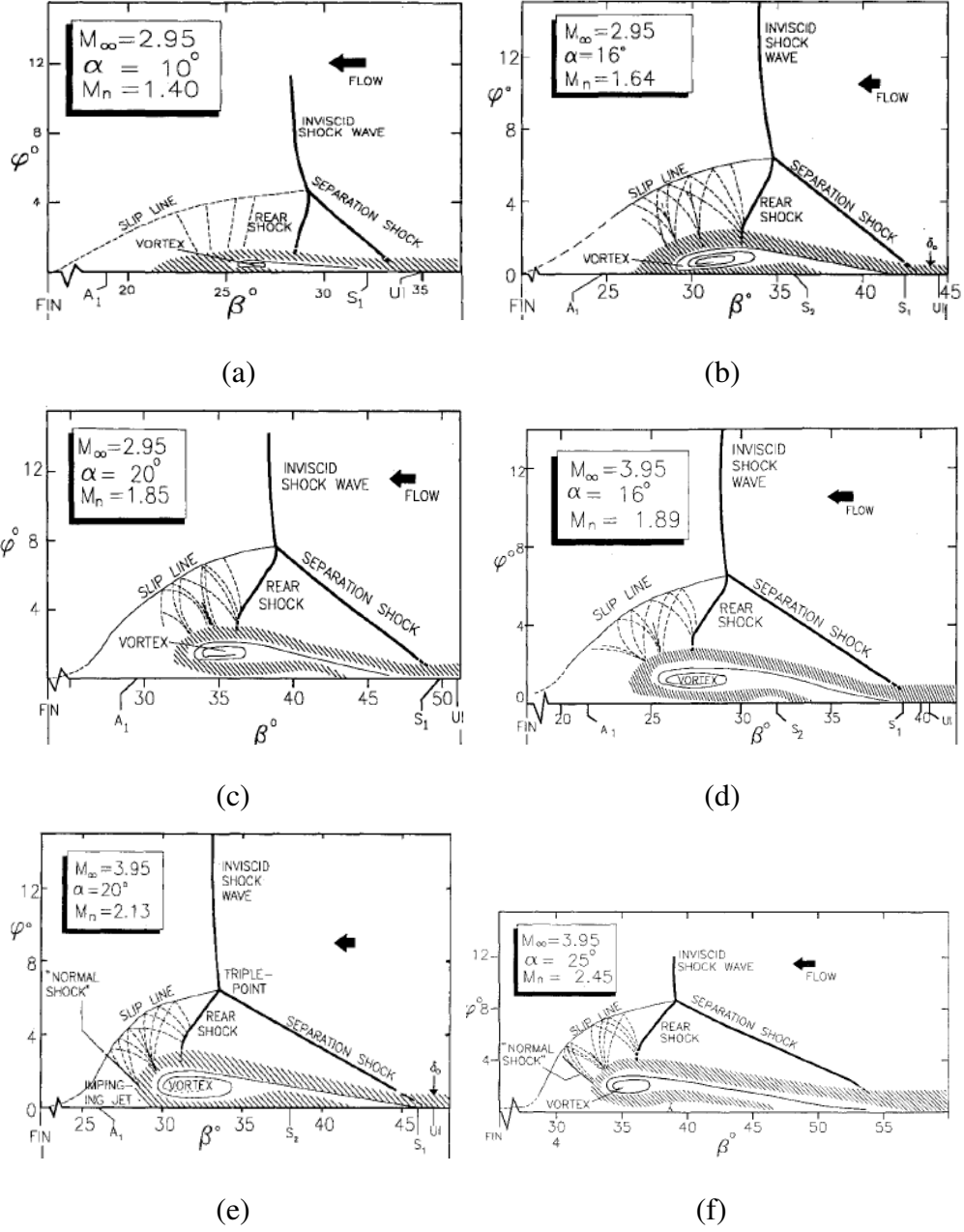


Figure A.1: Sketches of canonical flow structures (from Alvi and Settles [5]).

Appendix B: Arc and ray grids

Herein shown are the arc and ray grids used in the generation of the plots discussed in Ch. 5. For the TSP results, the grids are indicated by the gray arcs and rays superimposed over the given heat-flux distribution. For the schlieren results, the yellow arcs composing the grid are shown over a mean schlieren image.

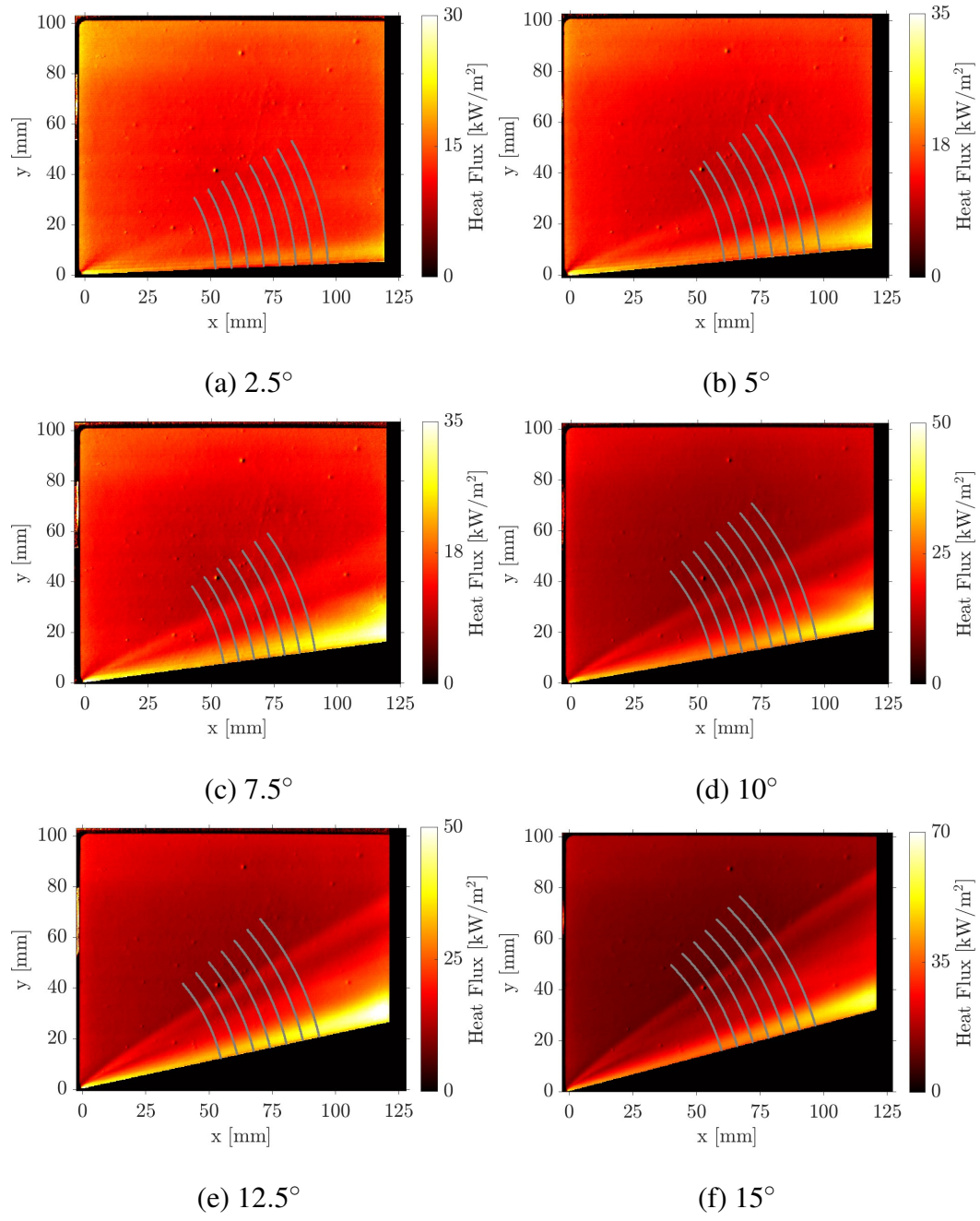


Figure B.1: VCO-centered arcs used in farfield grid generation.

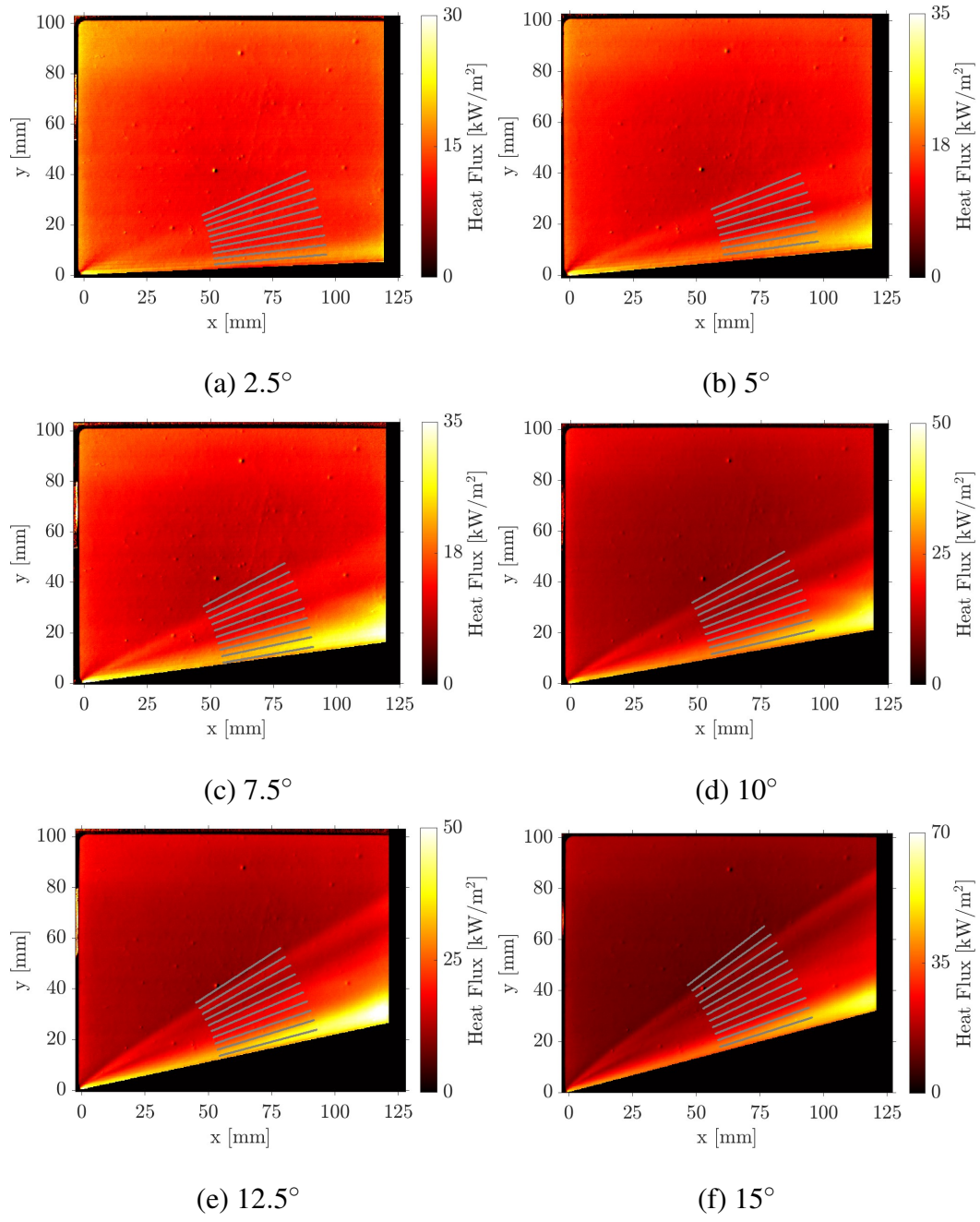


Figure B.2: VCO-emanating rays used in farfield grid generation.

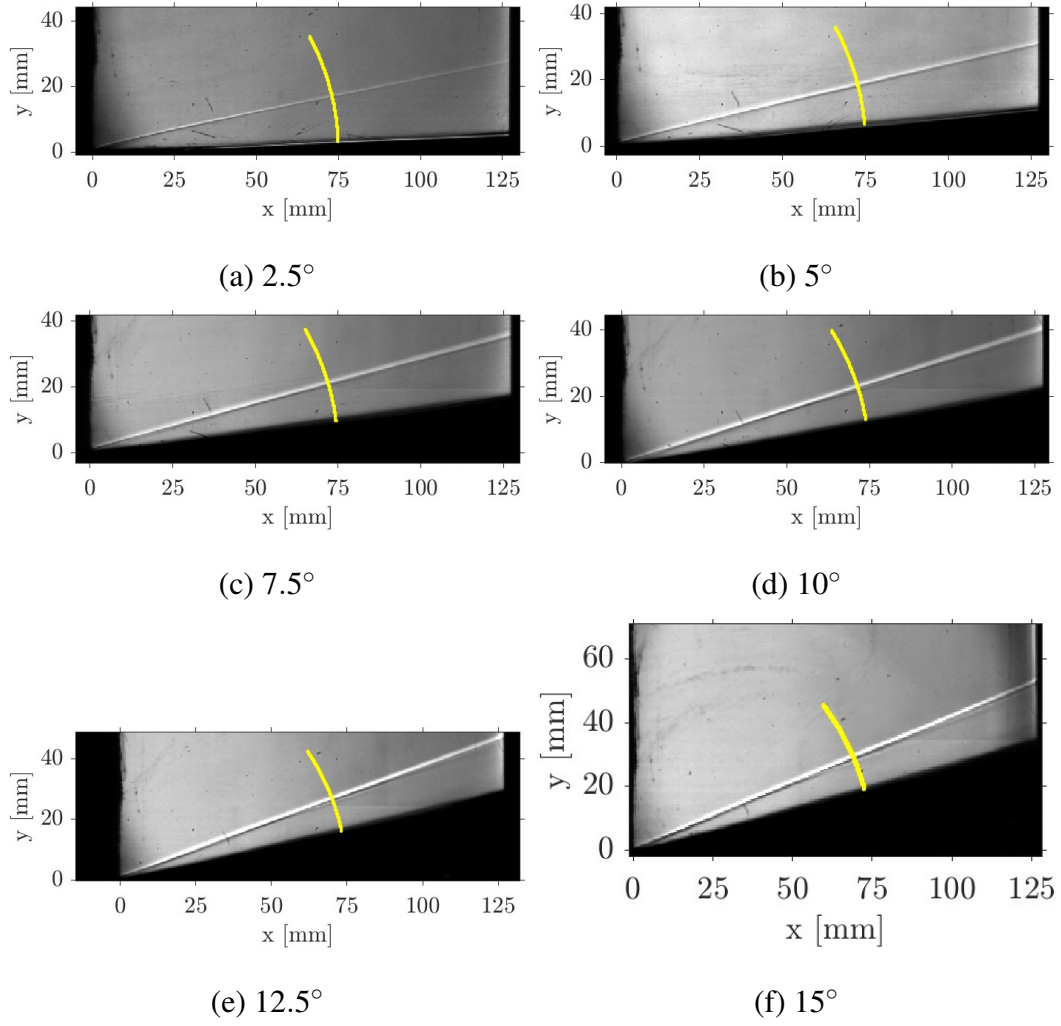


Figure B.3: Arcs used for schlieren power spectral density estimates.

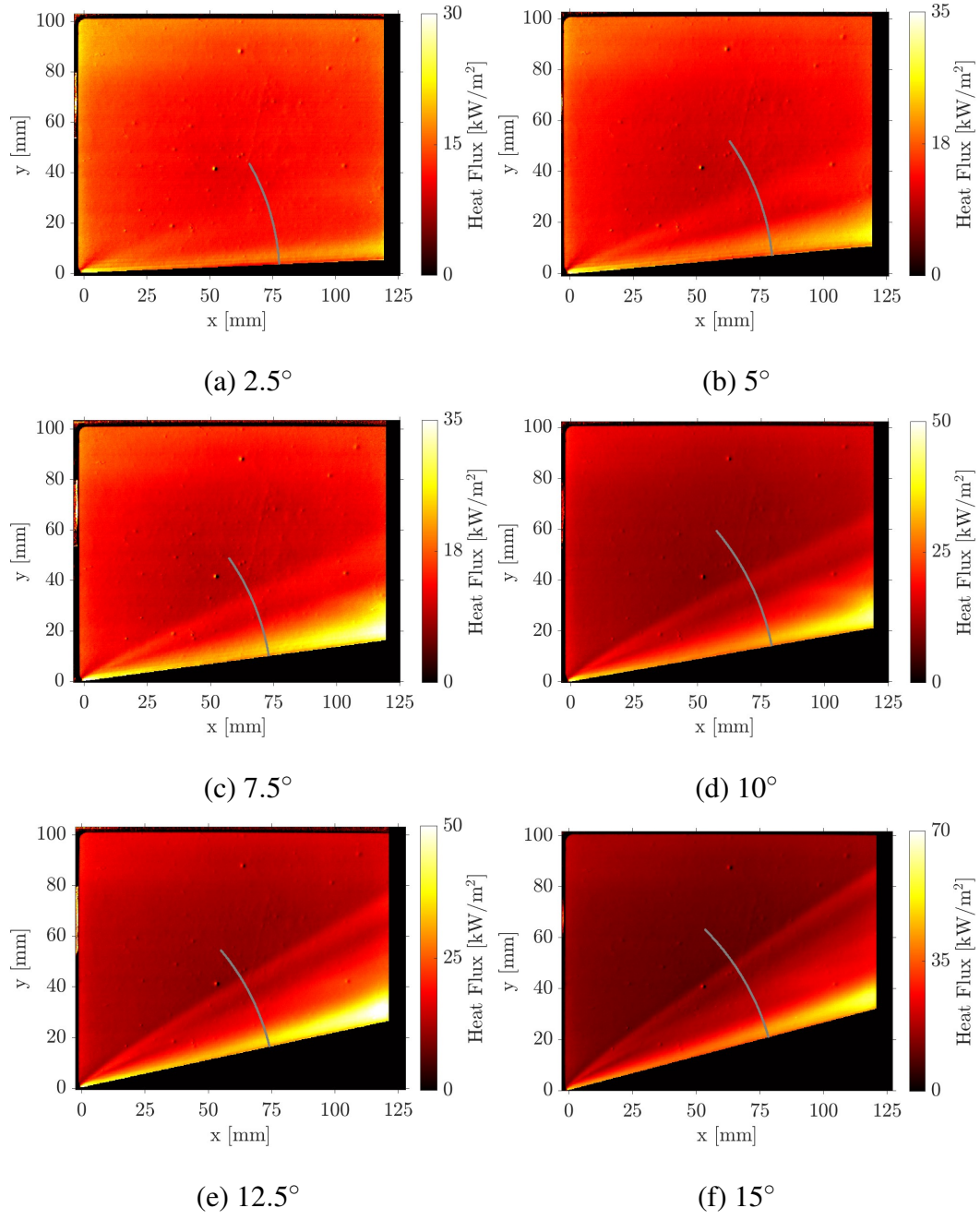


Figure B.4: Arcs used for heat flux versus azimuthal location versus time plots.

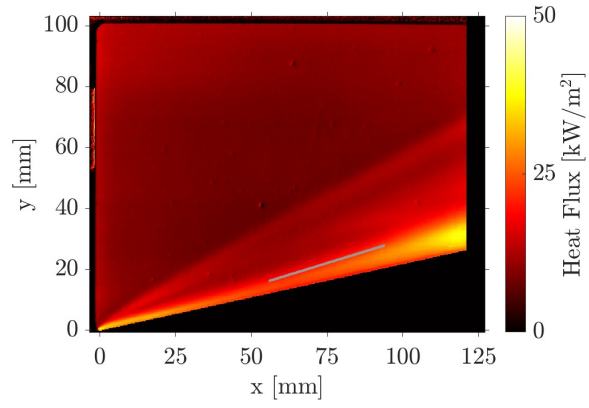


Figure B.5: Grid used for heat-flux versus radial distance from VCO versus time ($\alpha = 12.5^\circ$, condition B).

Appendix C: Temperature-change plots

Herein shown are the temperature changes over the steady test time for each fin angle and tunnel condition in the turbulent campaign. Note, the color scale is adjusted for each case.

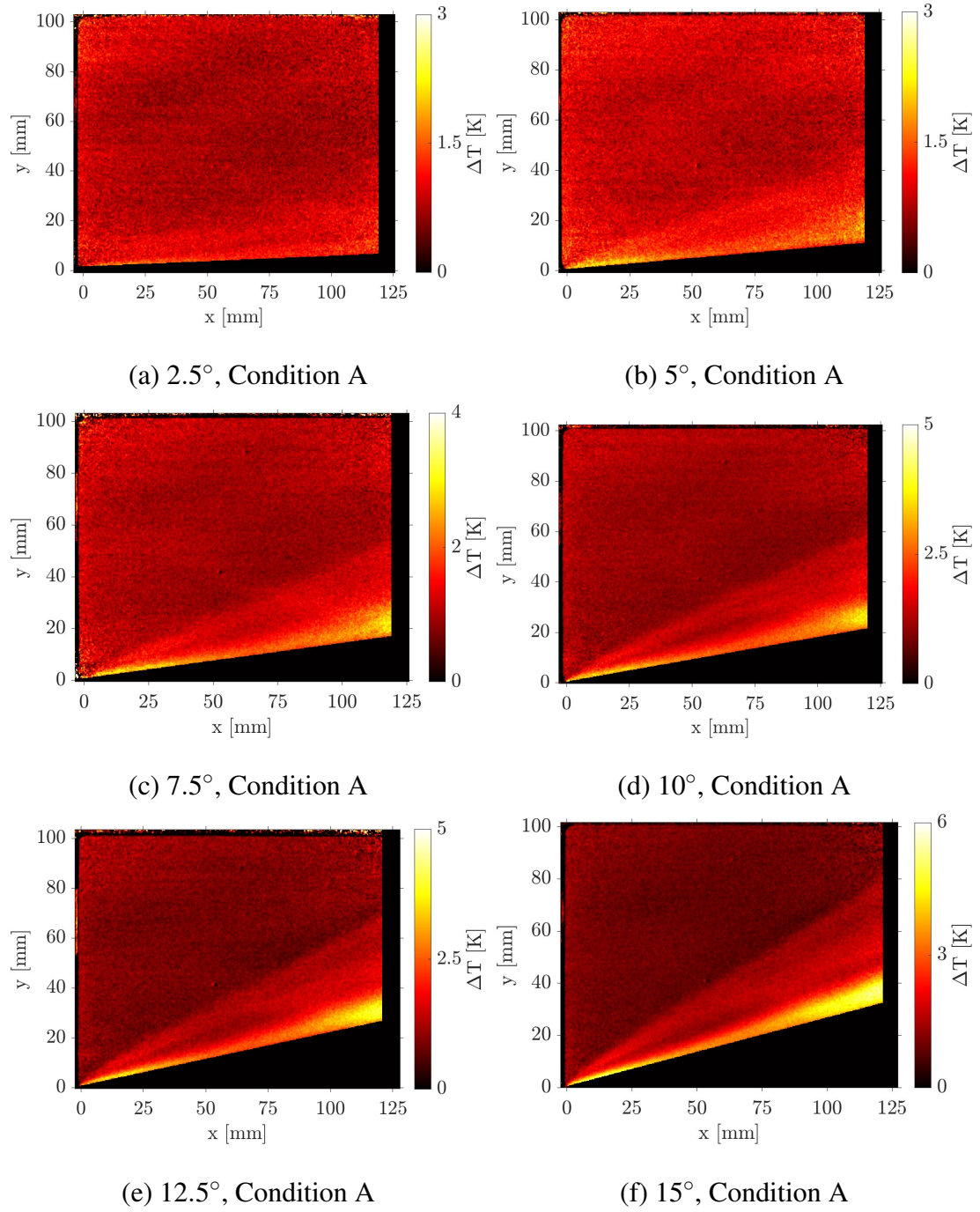
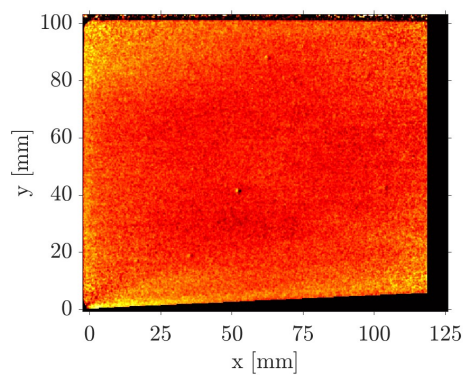
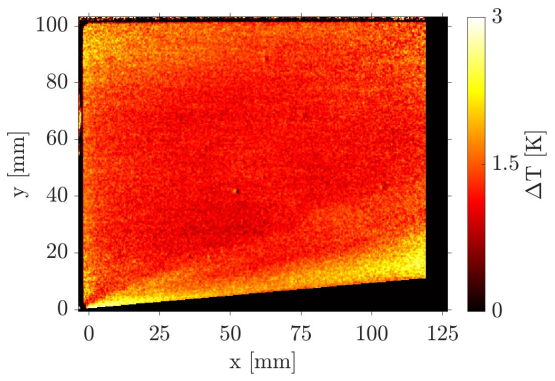


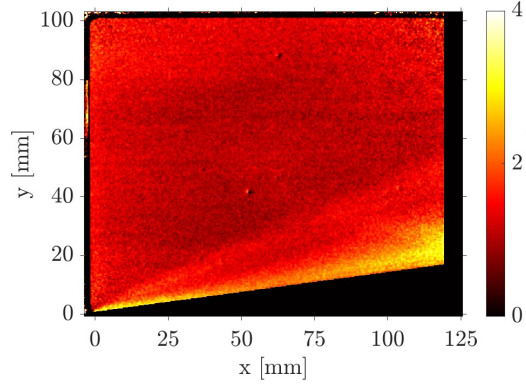
Figure C.1: Temperature change over steady test time (continued on the next page).



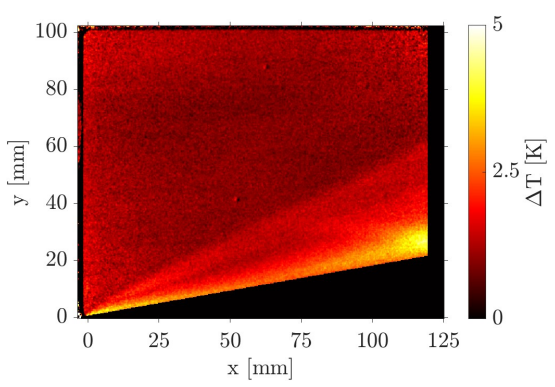
(g) 2.5°, Condition B



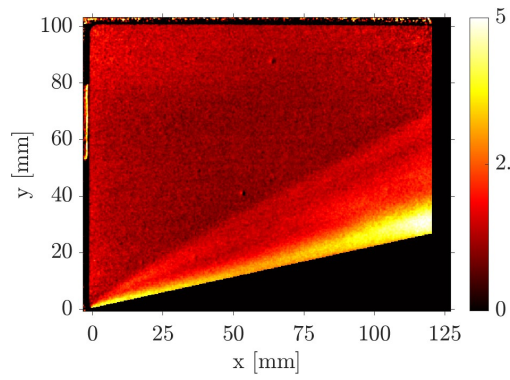
(h) 5°, Condition B



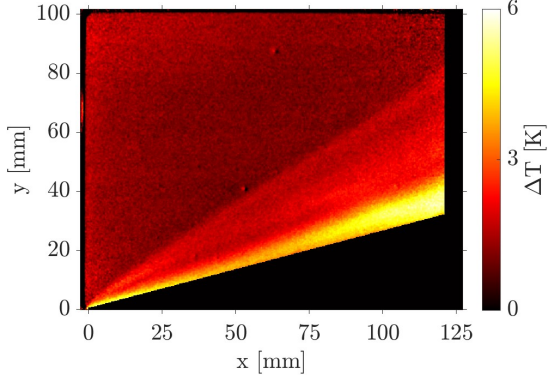
(i) 7.5°, Condition B



(j) 10°, Condition B

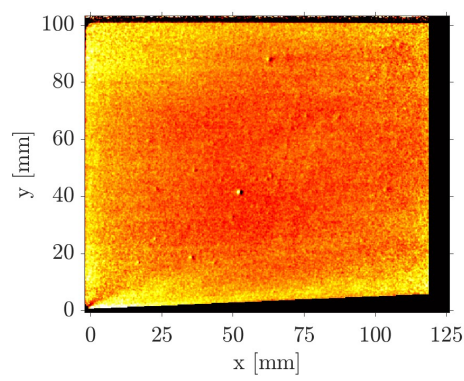


(k) 12.5°, Condition B

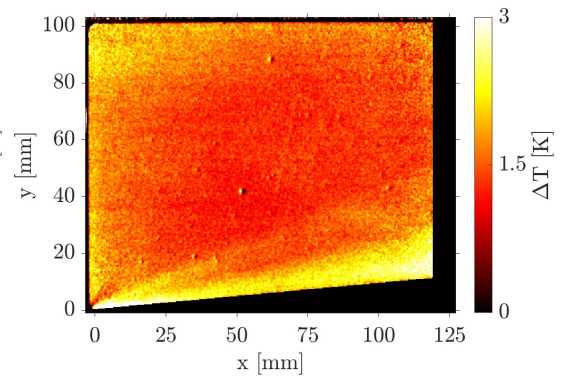


(l) 15°, Condition B

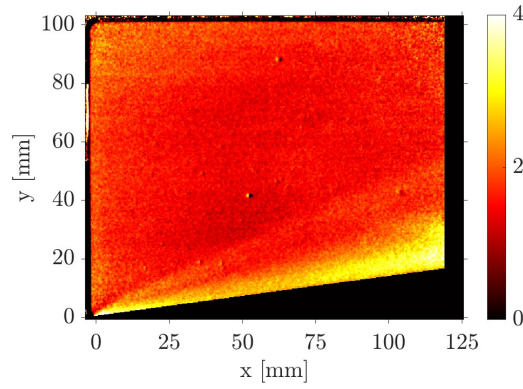
Figure C.1: (continued).



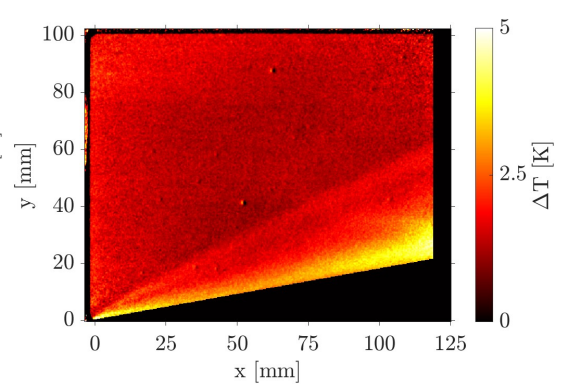
(m) 2.5°, Condition C



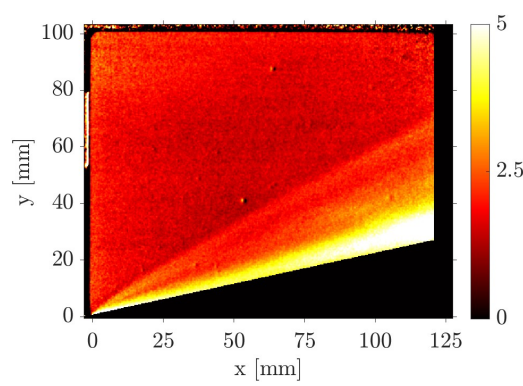
(n) 5°, Condition C



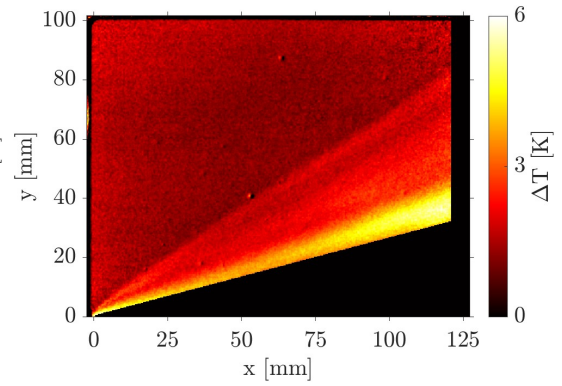
(o) 7.5°, Condition C



(p) 10°, Condition C



(q) 12.5°, Condition C



(r) 15°, Condition C

Figure C.1: (continued).

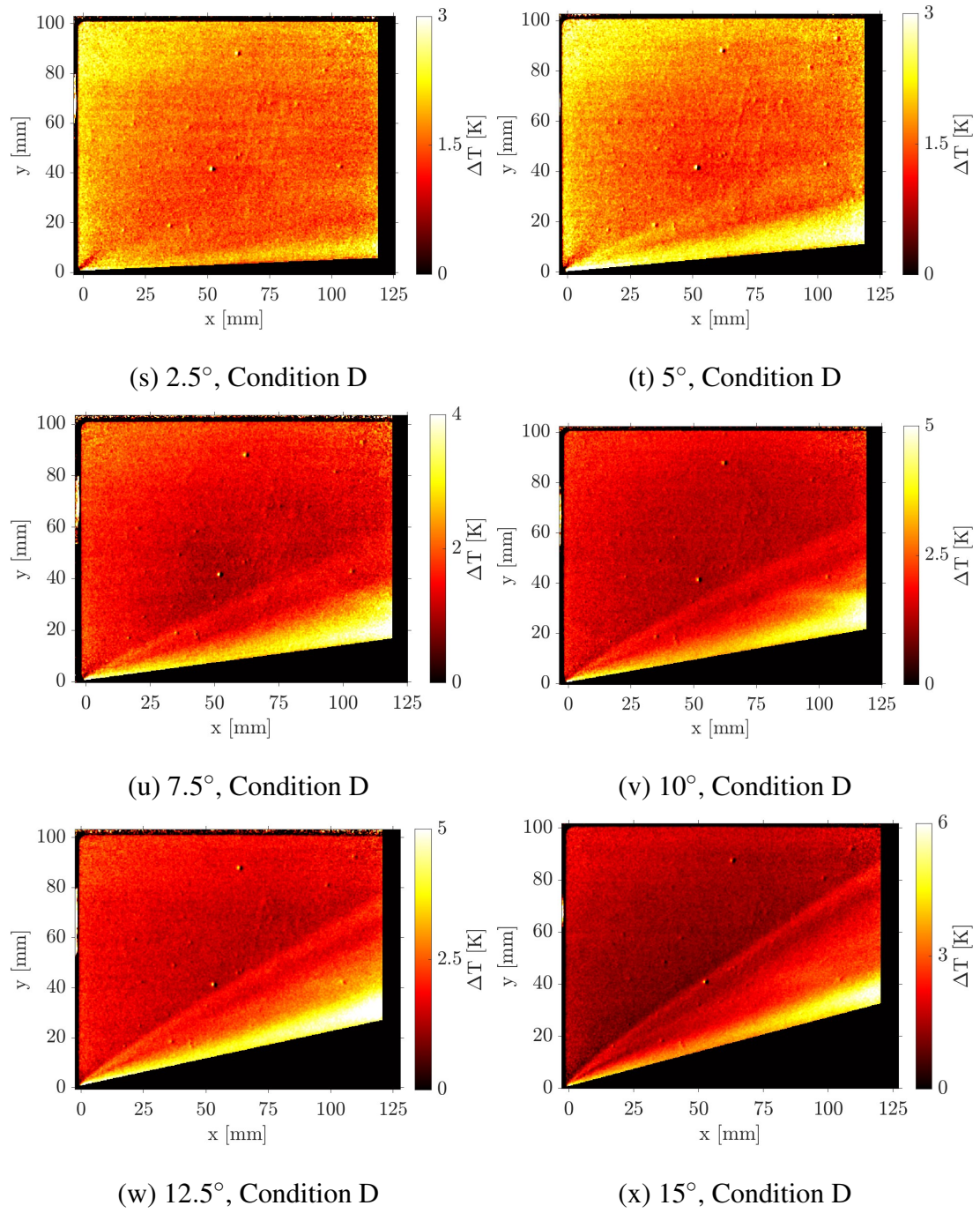


Figure C.1: (continued).

Appendix D: Analyses over entire parameter space

Herein shown are several of the analyses given in Ch. 5 over the entirety of the parameter space. Grids used in the generation of these plots are qualitatively similar to those provided in Appendix B.

D.1 Temperature-sensitive paint

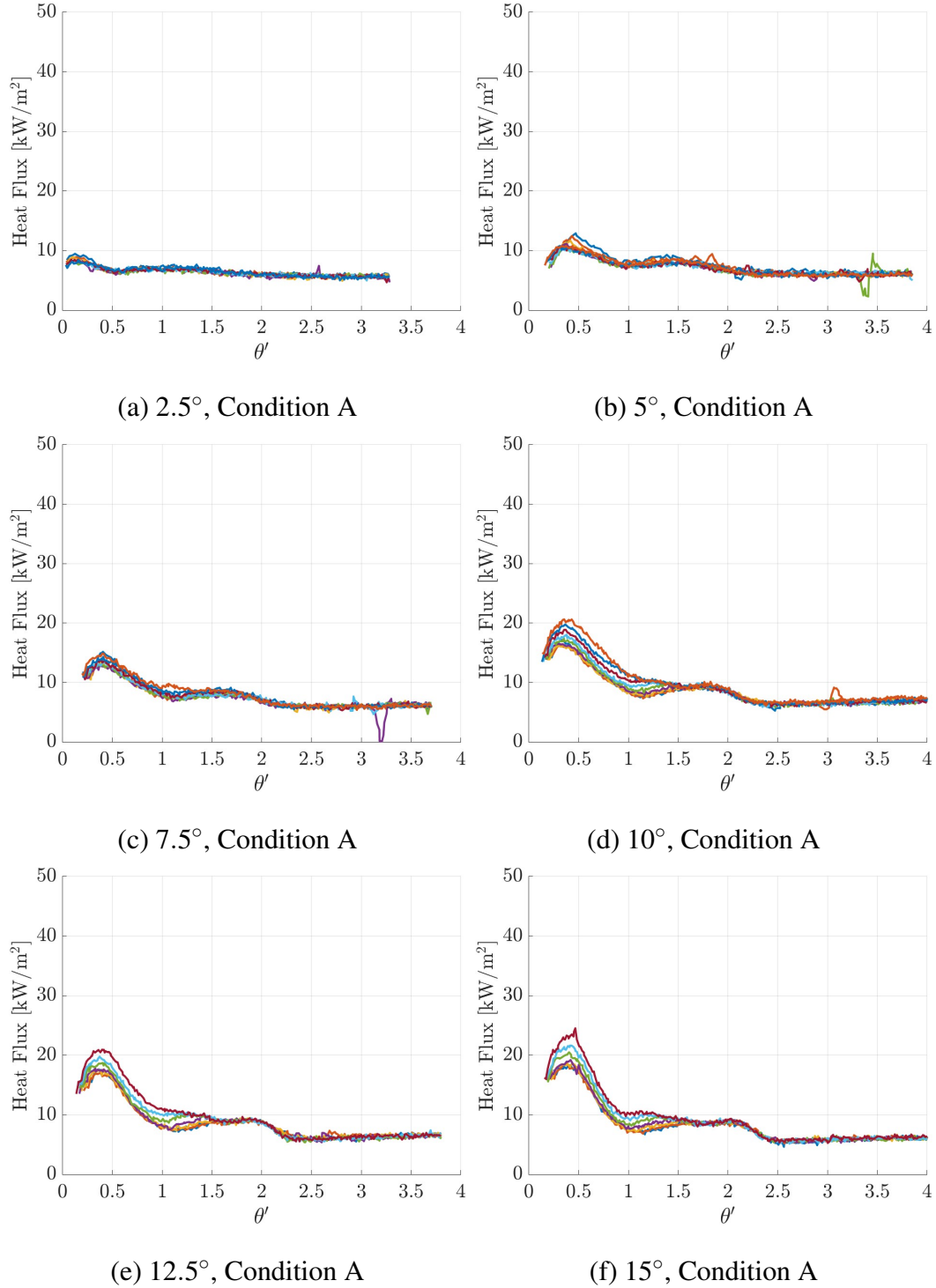
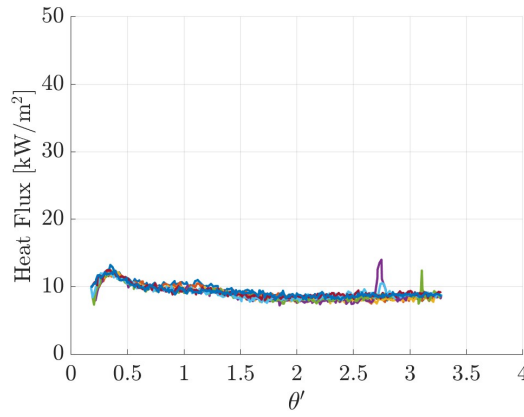
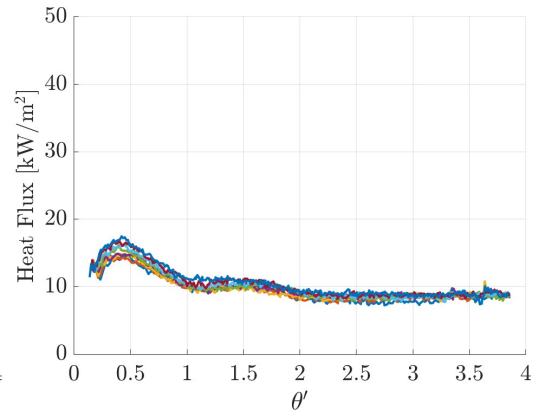


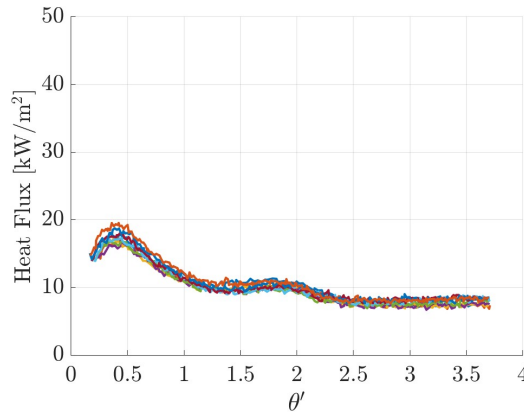
Figure D.1: Heat-flux distribution along arcs centered about the VCO for each fin angle (continued on the next page).



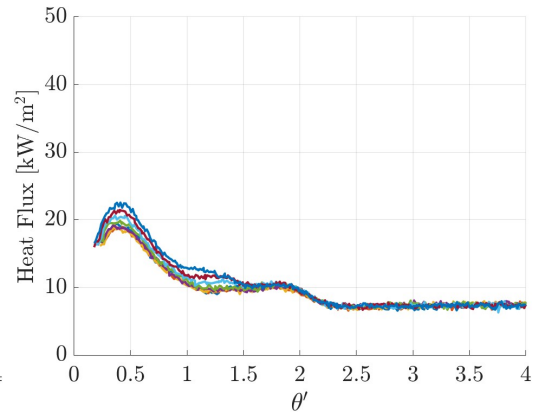
(g) 2.5°, Condition B



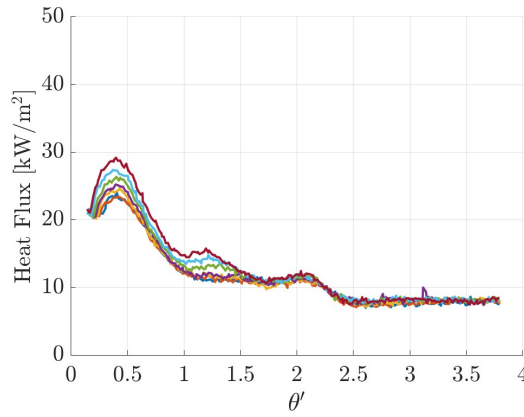
(h) 5°, Condition B



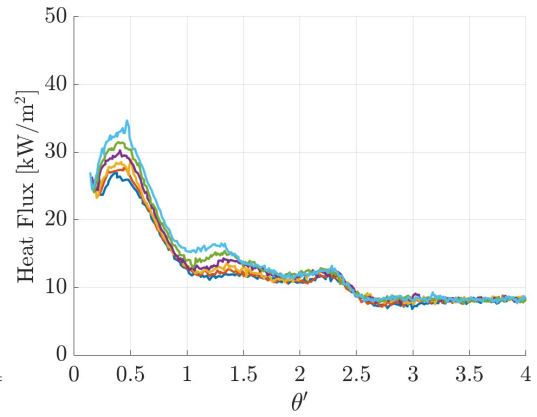
(i) 7.5°, Condition B



(j) 10°, Condition B

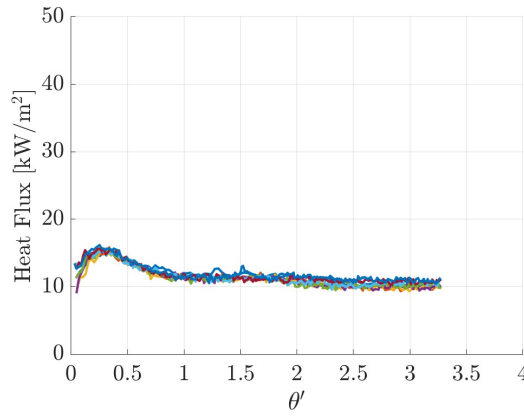


(k) 12.5°, Condition B

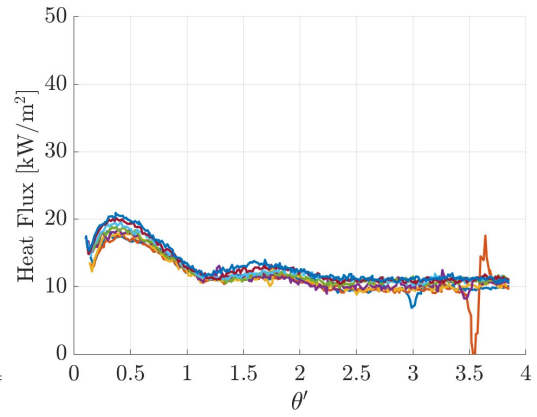


(l) 15°, Condition B

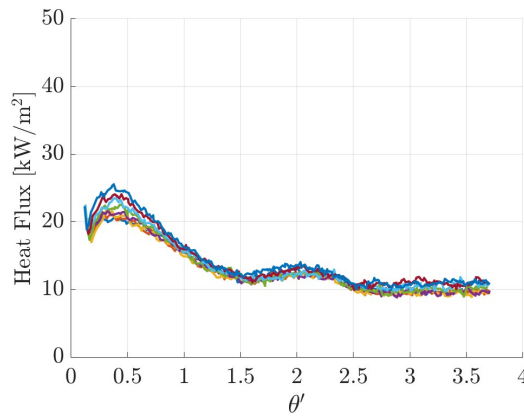
Figure D.1: (continued).



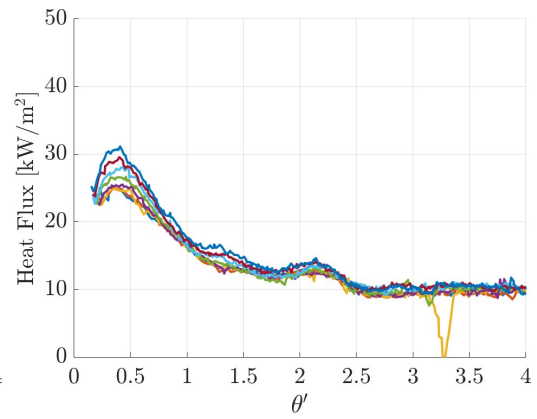
(m) 2.5°, Condition C



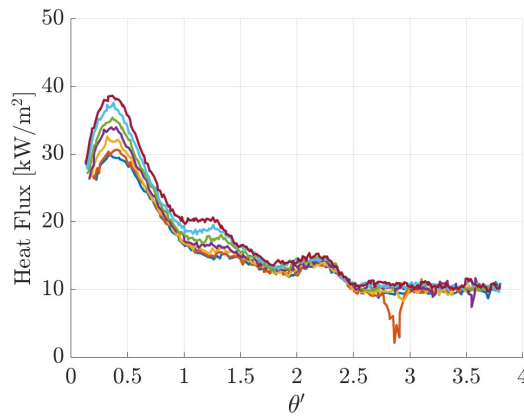
(n) 5°, Condition C



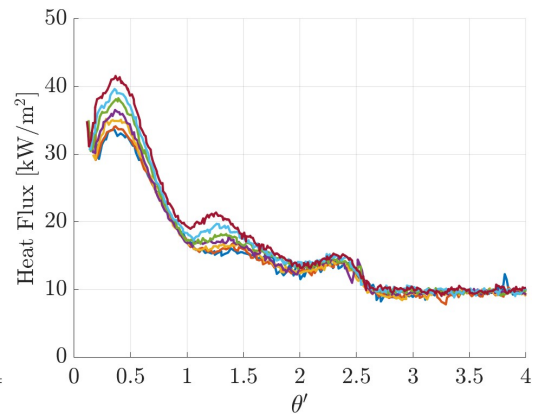
(o) 7.5°, Condition C



(p) 10°, Condition C

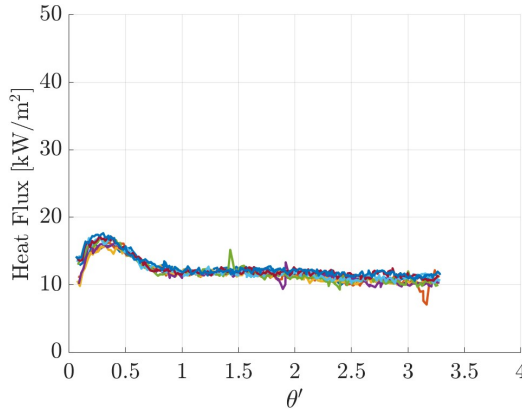


(q) 12.5°, Condition C

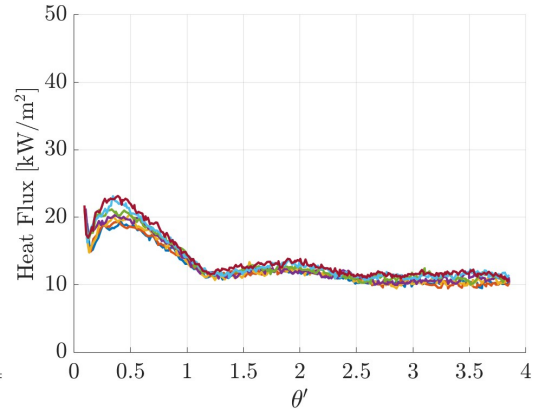


(r) 15°, Condition C

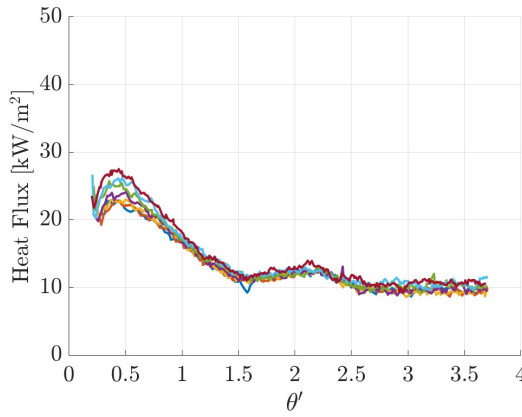
Figure D.1: (continued).



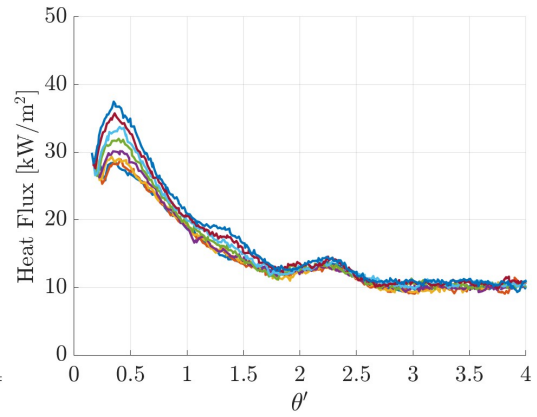
(s) 2.5°, Condition D



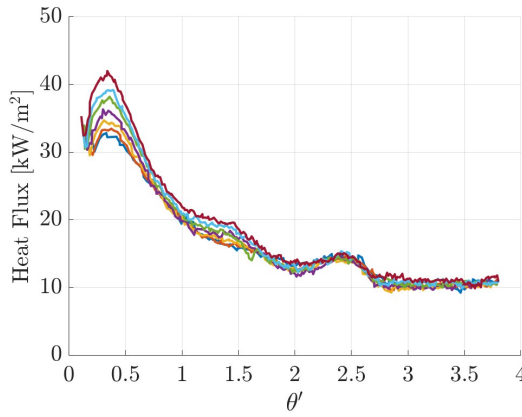
(t) 5°, Condition D



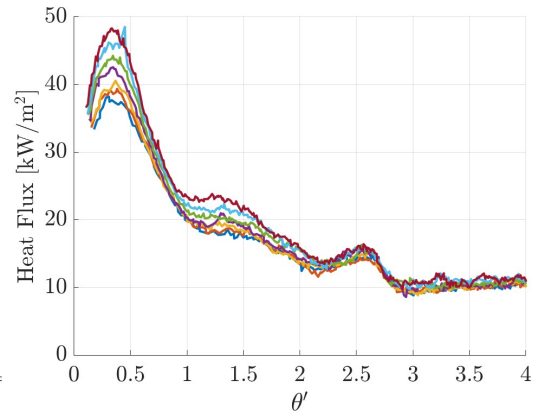
(u) 7.5°, Condition D



(v) 10°, Condition D

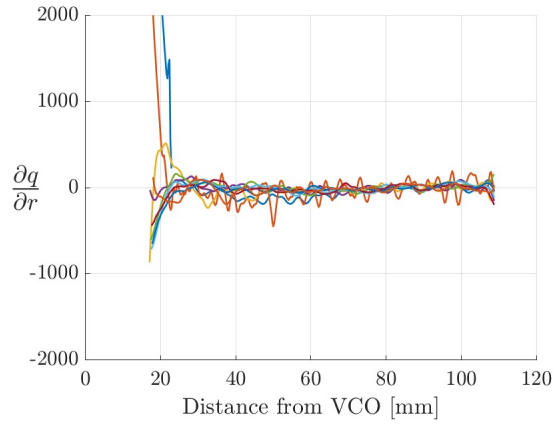


(w) 12.5°, Condition D

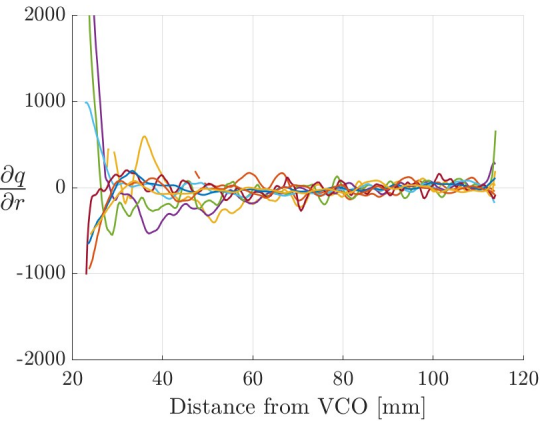


(x) 15°, Condition D

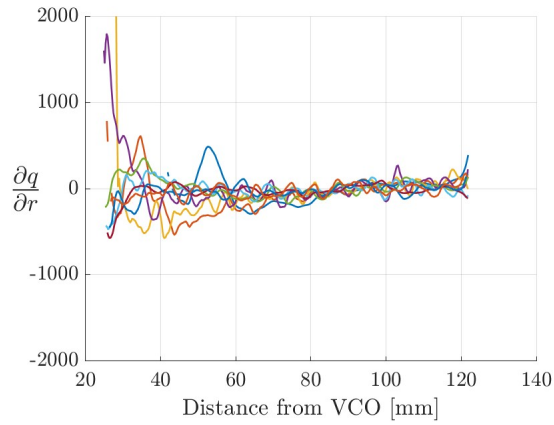
Figure D.1: (continued).



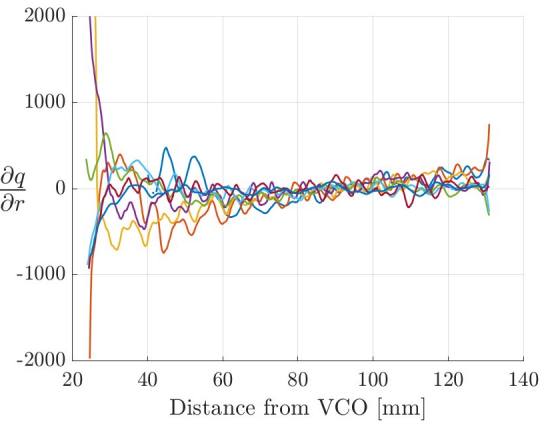
(a) 2.5°, Condition A



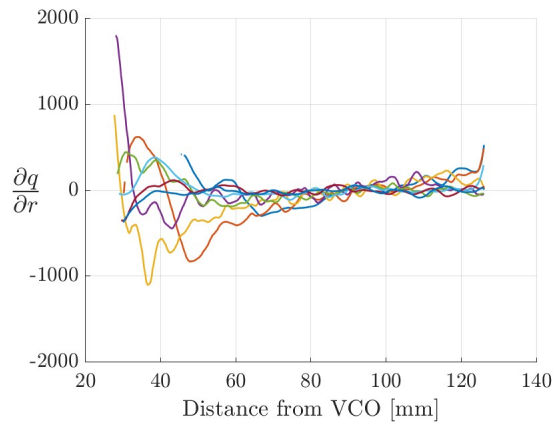
(b) 5°, Condition A



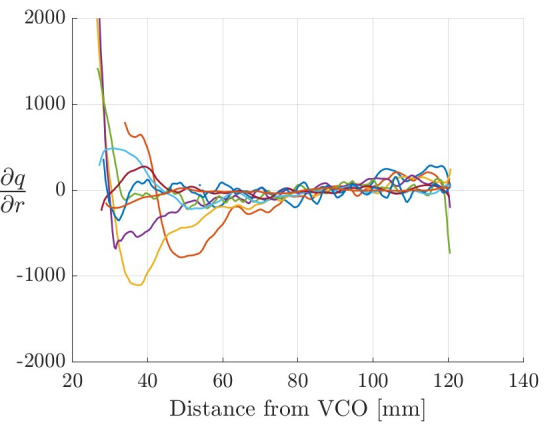
(c) 7.5°, Condition A



(d) 10°, Condition A

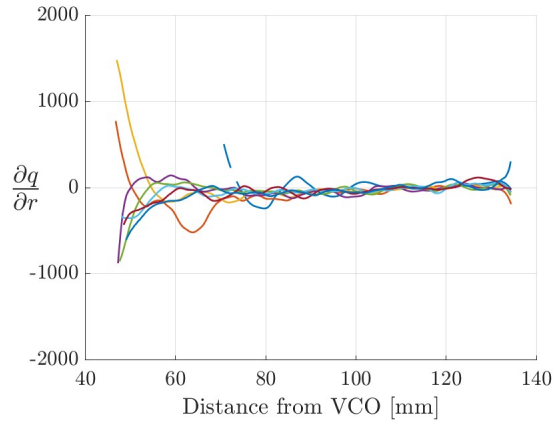


(e) 12.5°, Condition A

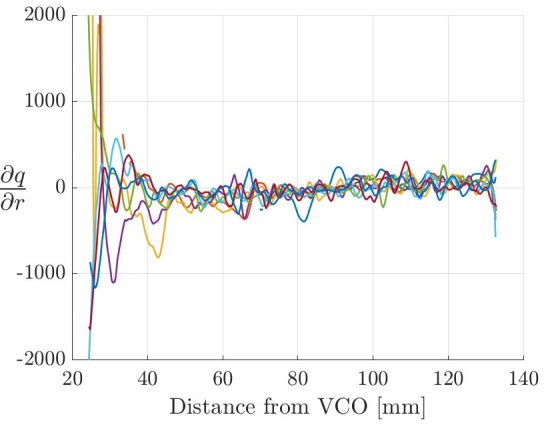


(f) 15°, Condition A

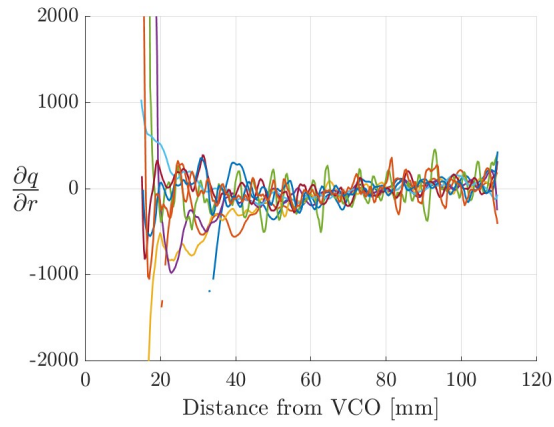
Figure D.2: Radial derivatives of heat-flux distributions along rays originating at VCO (continued on the next page).



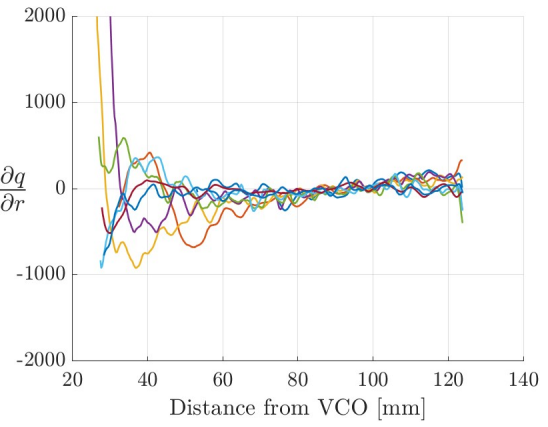
(g) 2.5°, Condition B



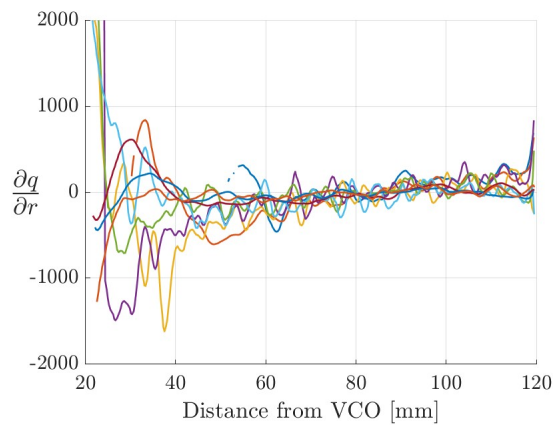
(h) 5°, Condition B



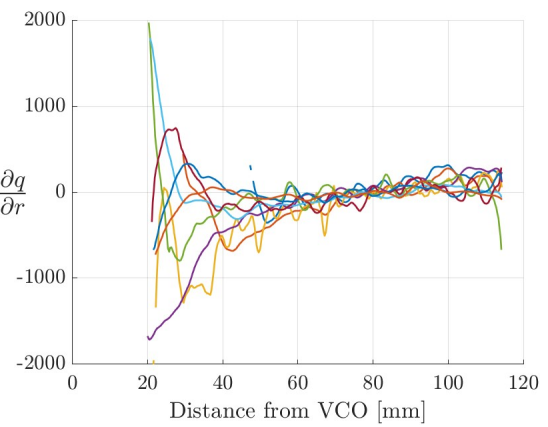
(i) 7.5°, Condition B



(j) 10°, Condition B

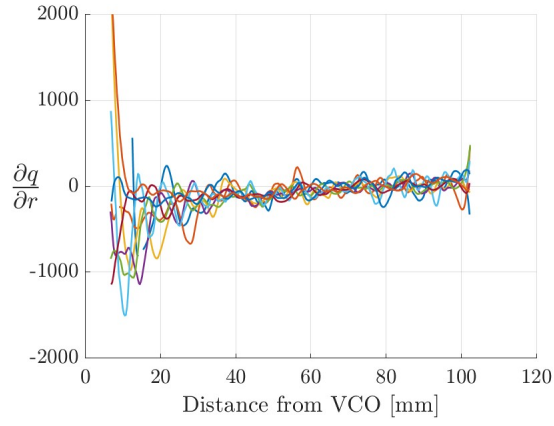


(k) 12.5°, Condition B

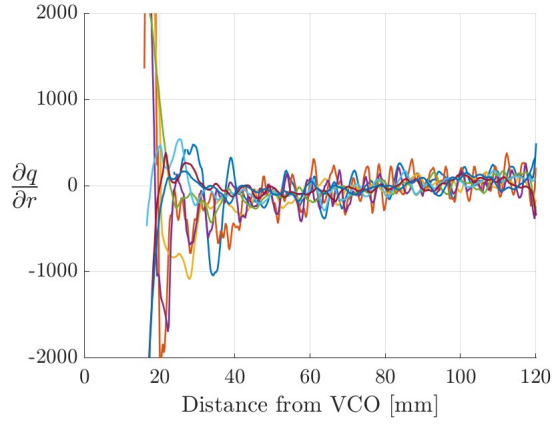


(l) 15°, Condition B

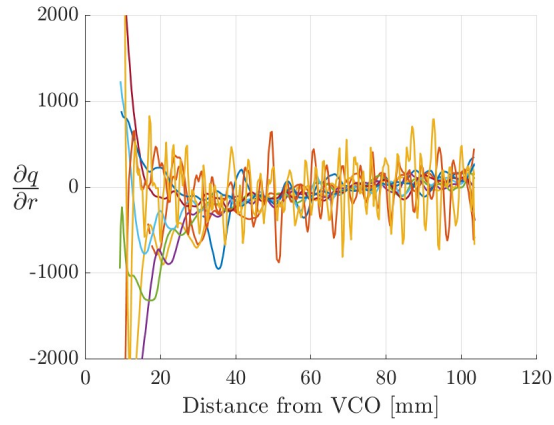
Figure D.2: (continued).



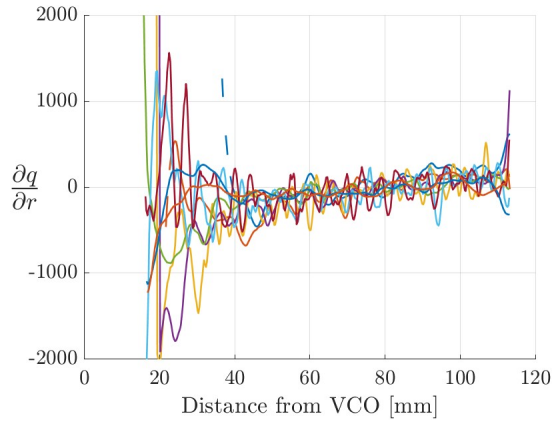
(m) 2.5° , Condition C



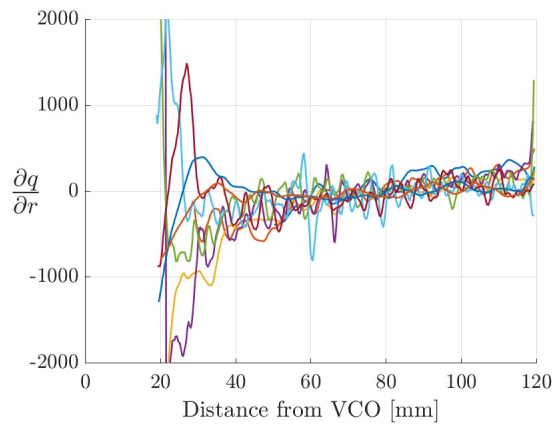
(n) 5° , Condition C



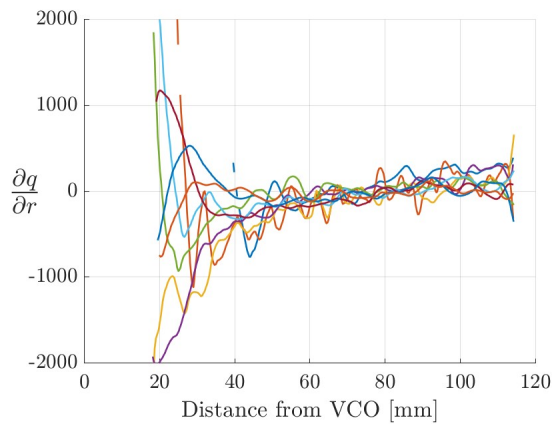
(o) 7.5° , Condition C



(p) 10° , Condition C

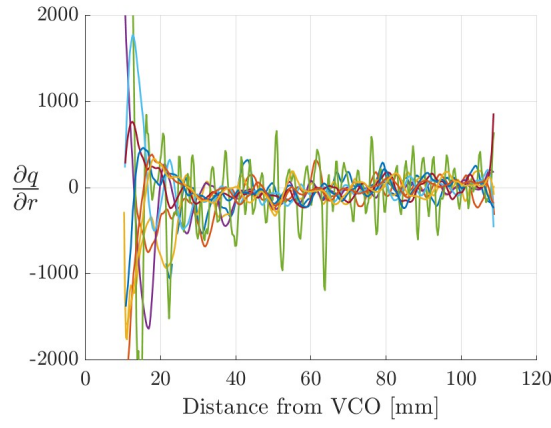


(q) 12.5° , Condition C

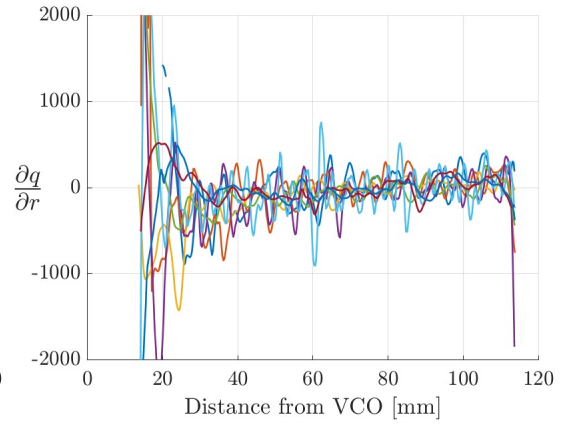


(r) 15° , Condition C

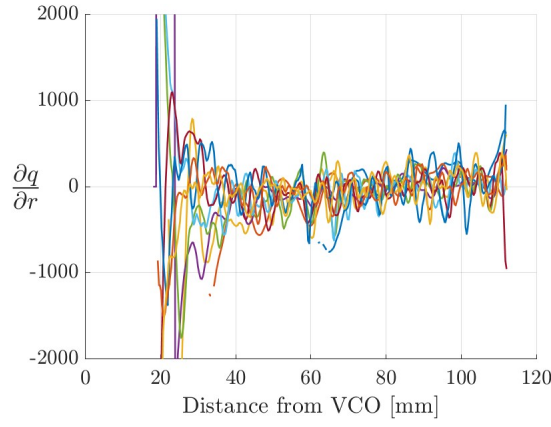
Figure D.2: (continued).



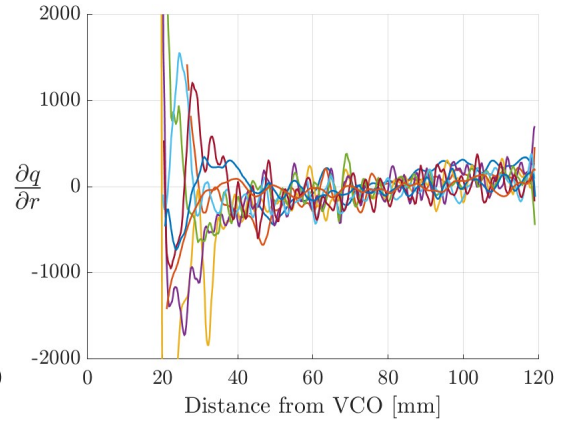
(s) 2.5°, Condition D



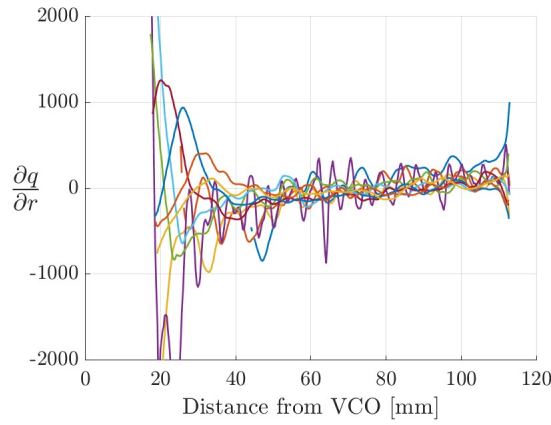
(t) 5°, Condition D



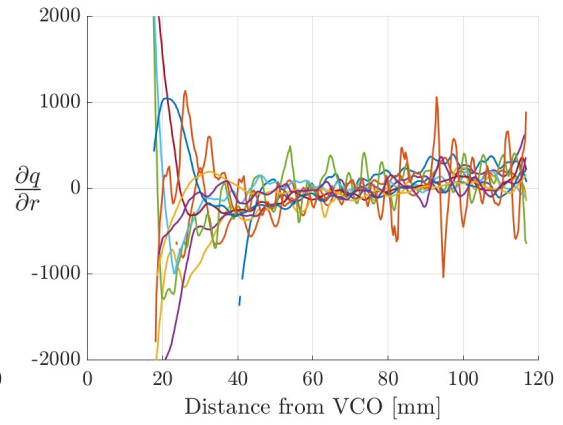
(u) 7.5°, Condition D



(v) 10°, Condition D



(w) 12.5°, Condition D



(x) 15°, Condition D

Figure D.2: (continued).

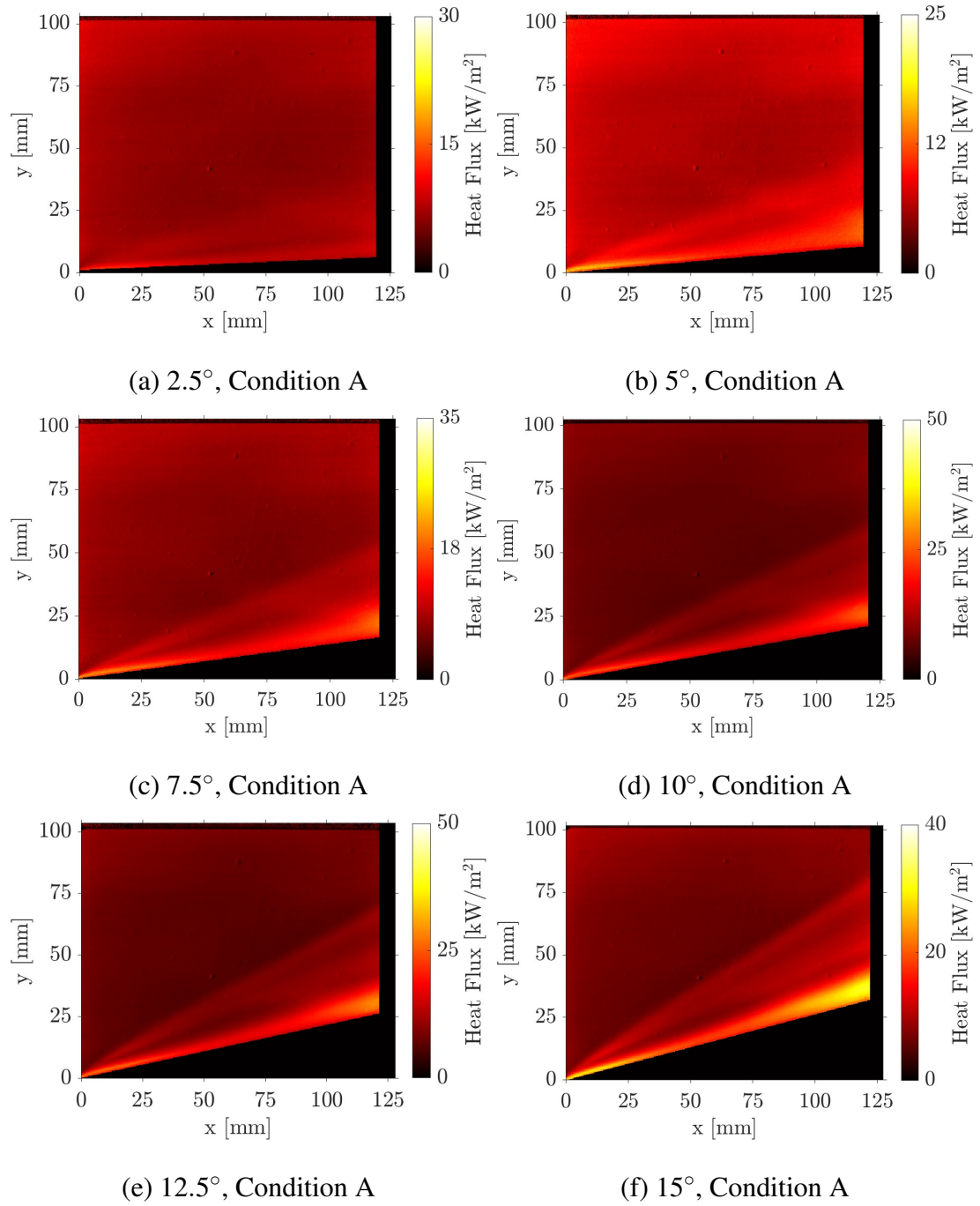
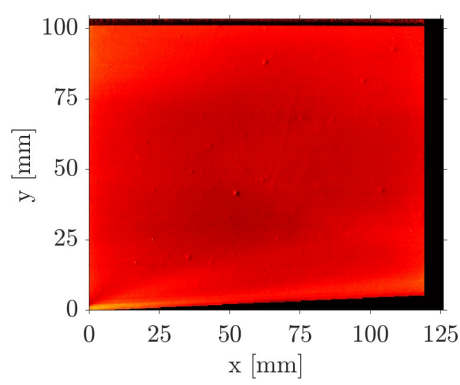
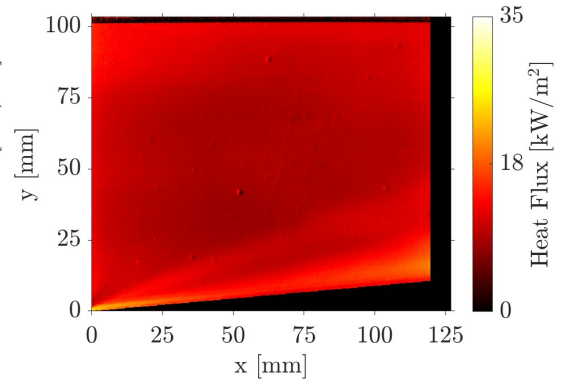


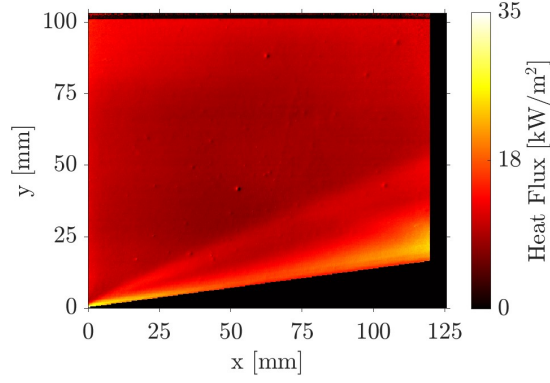
Figure D.3: Mean heat-flux distribution for each fin angle (continued on the next page).



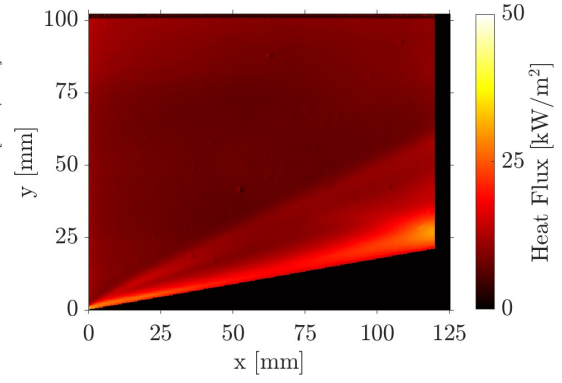
(g) 2.5°, Condition B



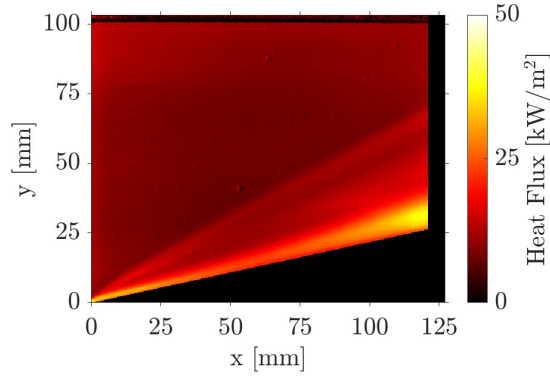
(h) 5°, Condition B



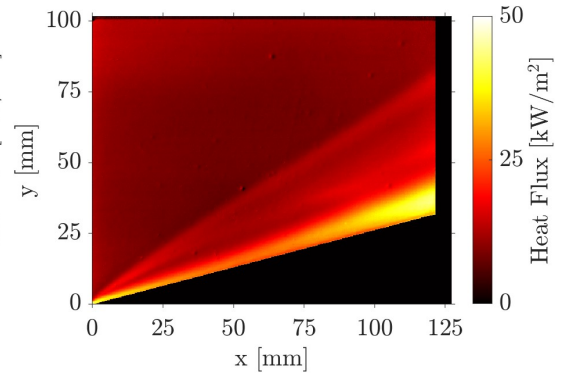
(i) 7.5°, Condition B



(j) 10°, Condition B



(k) 12.5°, Condition B



(l) 15°, Condition B

Figure D.3: (continued).

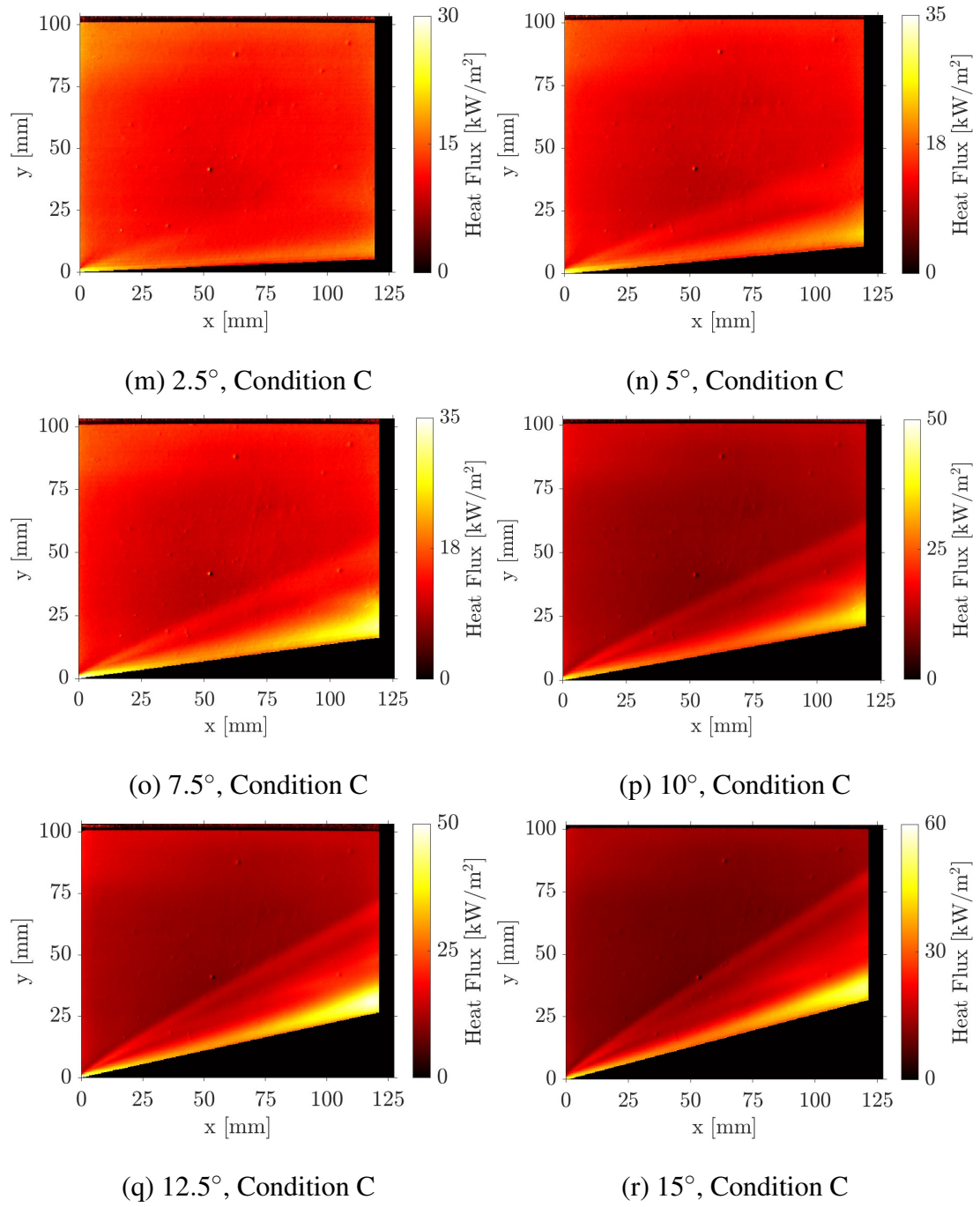


Figure D.3: (continued).

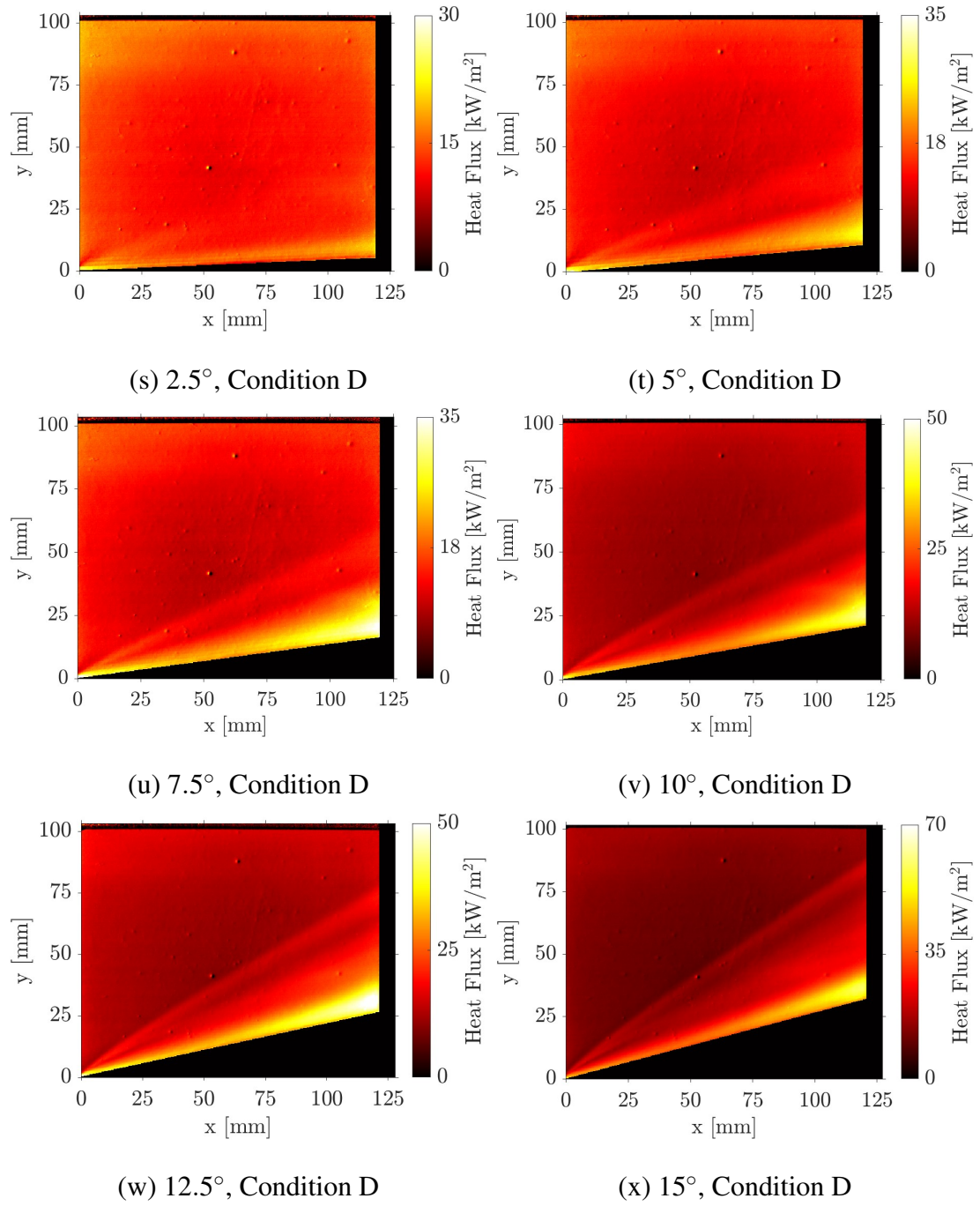
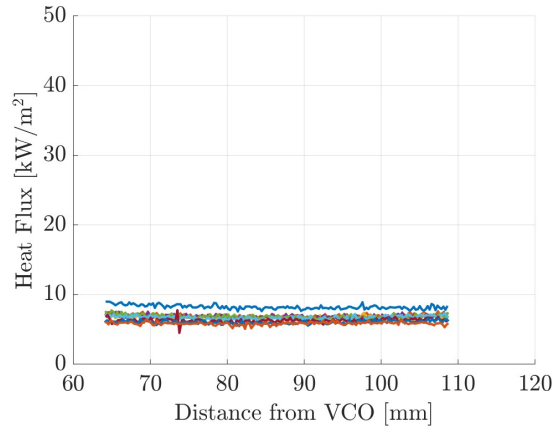
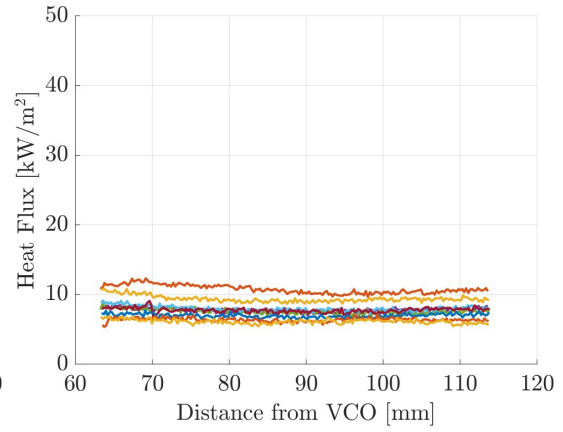


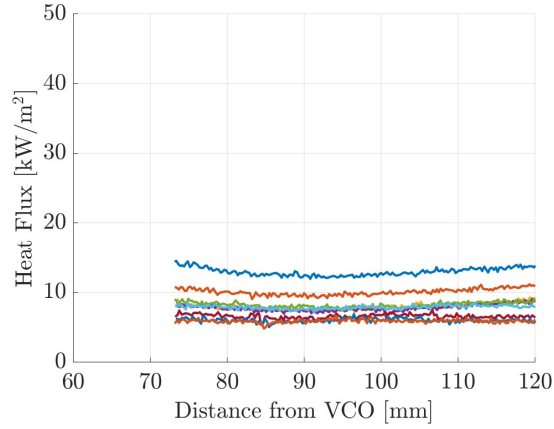
Figure D.3: (continued).



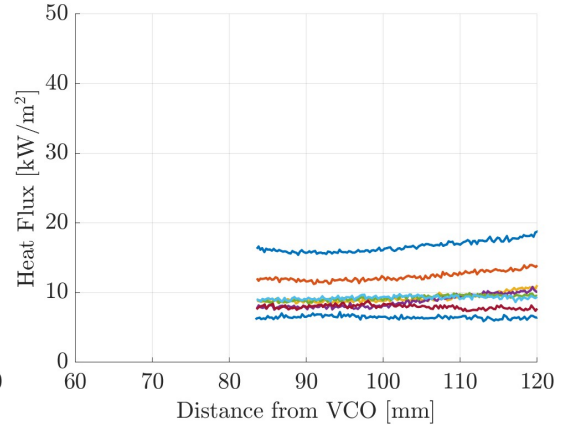
(a) 2.5°, Condition A



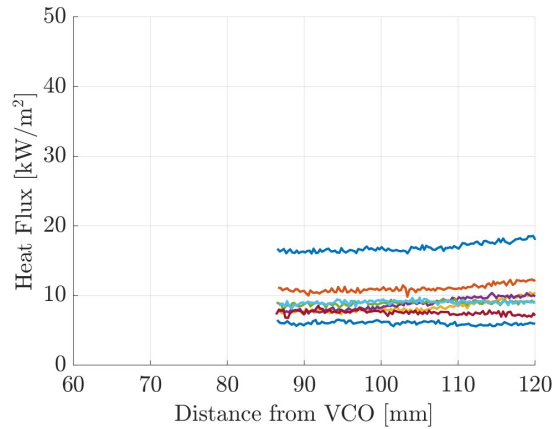
(b) 5°, Condition A



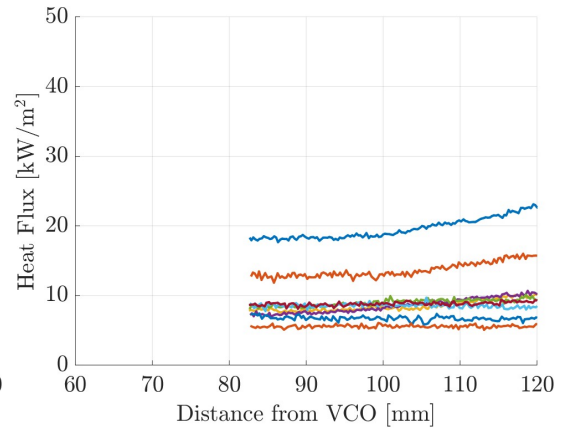
(c) 7.5°, Condition A



(d) 10°, Condition A

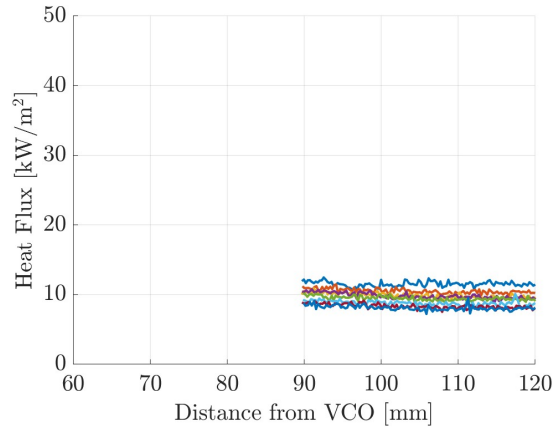


(e) 12.5°, Condition A

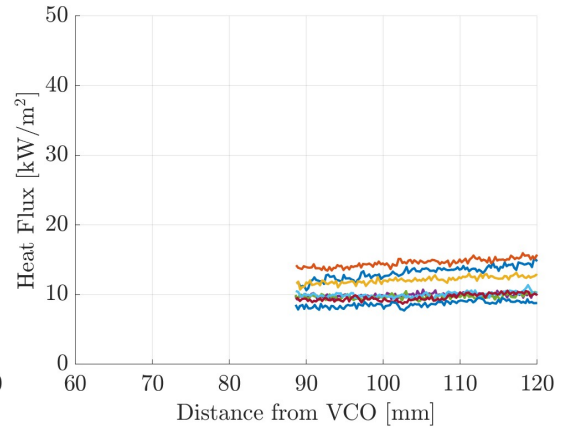


(f) 15°, Condition A

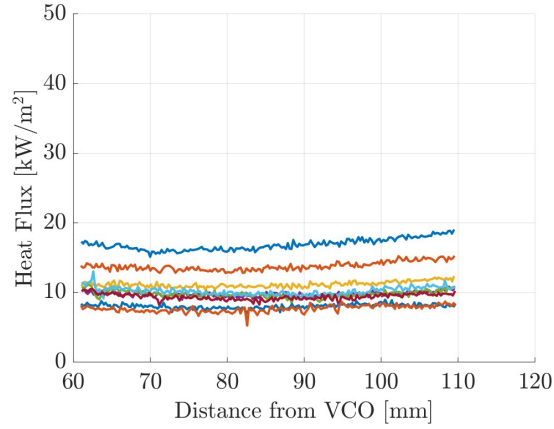
Figure D.4: Heat-flux distribution along rays emanating from the VCO for each fin angle (continued on the next page).



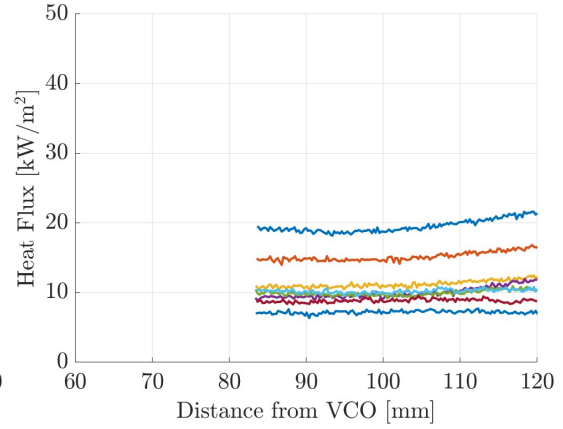
(g) 2.5°, Condition B



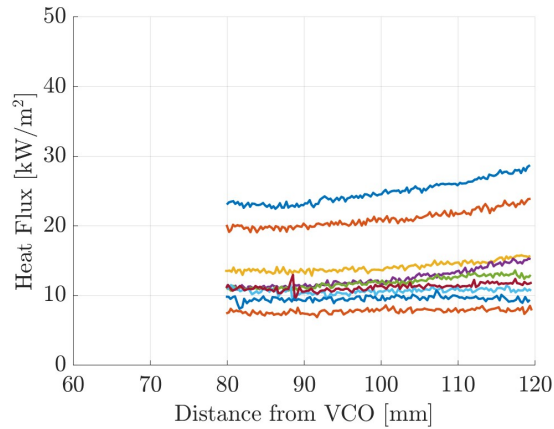
(h) 5°, Condition B



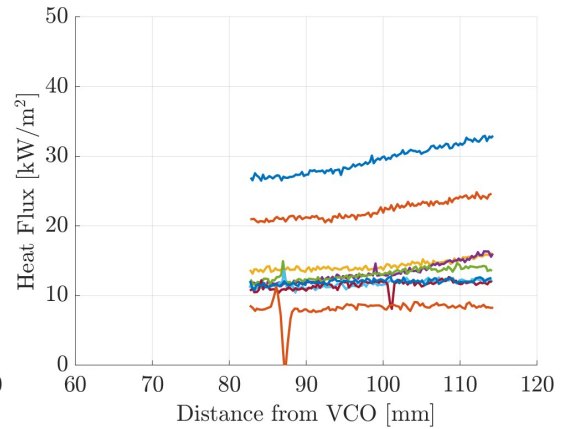
(i) 7.5°, Condition B



(j) 10°, Condition B

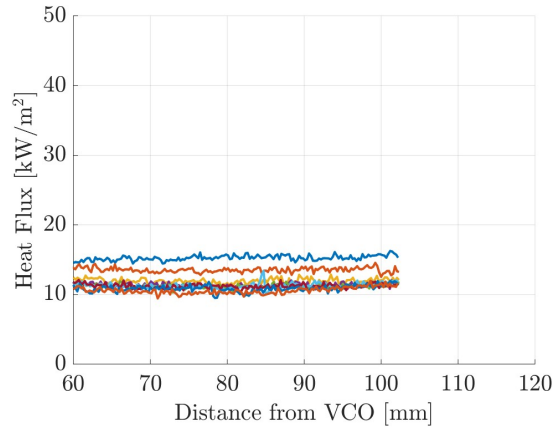


(k) 12.5°, Condition B

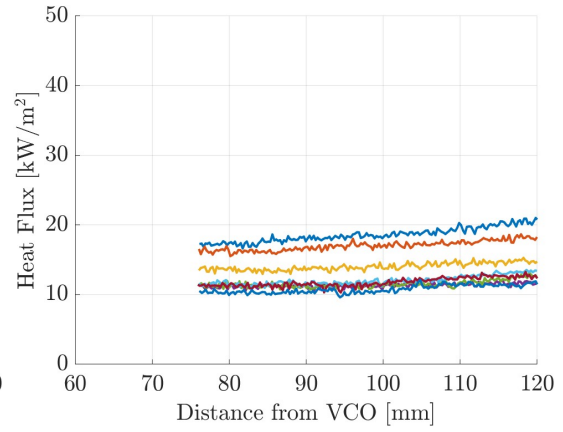


(l) 15°, Condition B

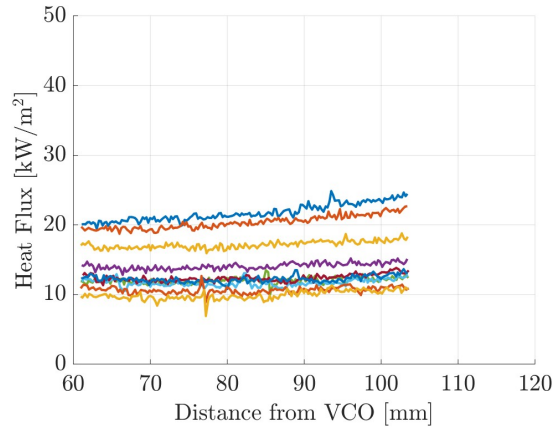
Figure D.4: (continued).



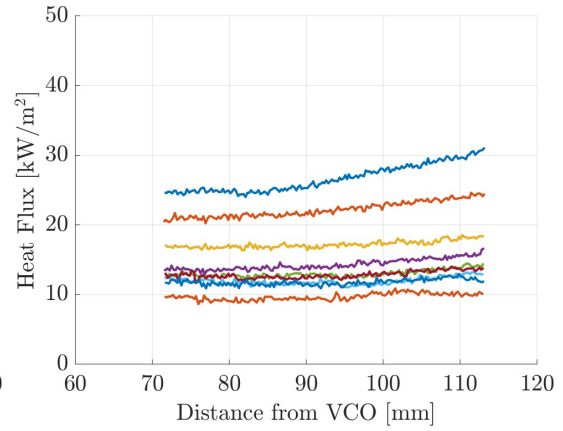
(m) 2.5°, Condition C



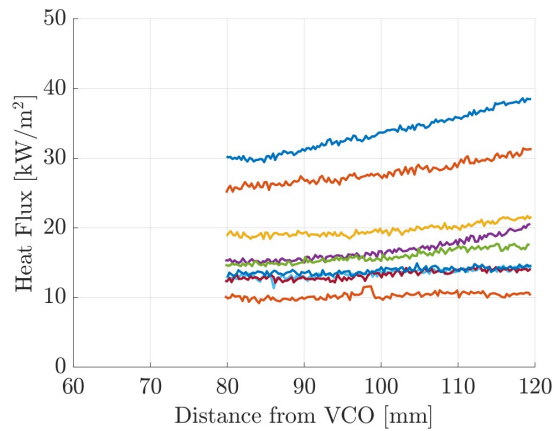
(n) 5°, Condition C



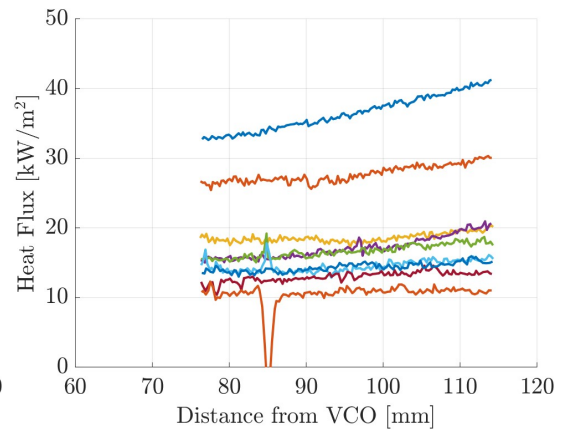
(o) 7.5°, Condition C



(p) 10°, Condition C

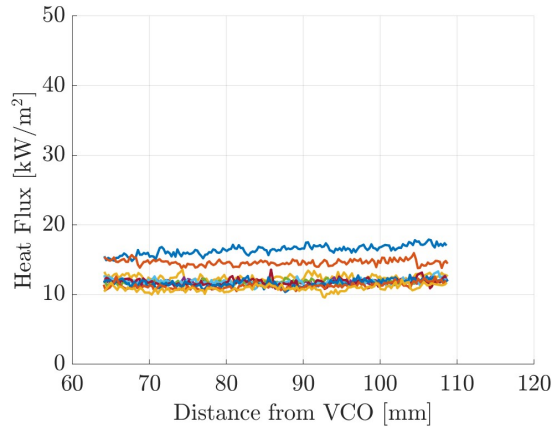


(q) 12.5°, Condition C

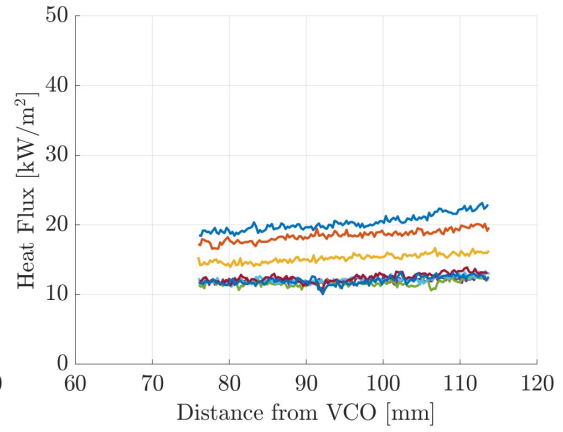


(r) 15°, Condition C

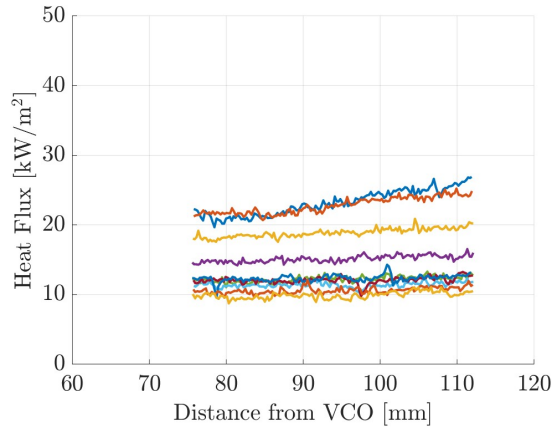
Figure D.4: (continued).



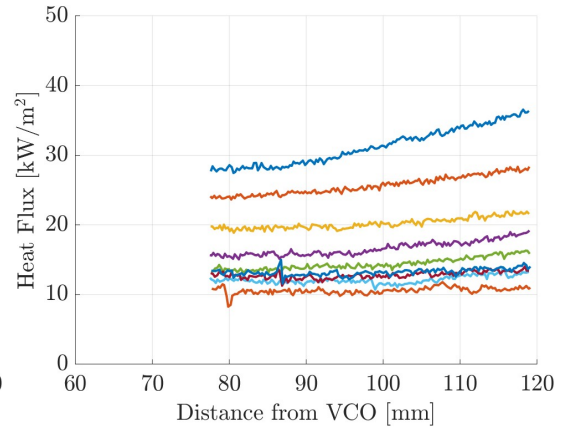
(s) 2.5°, Condition D



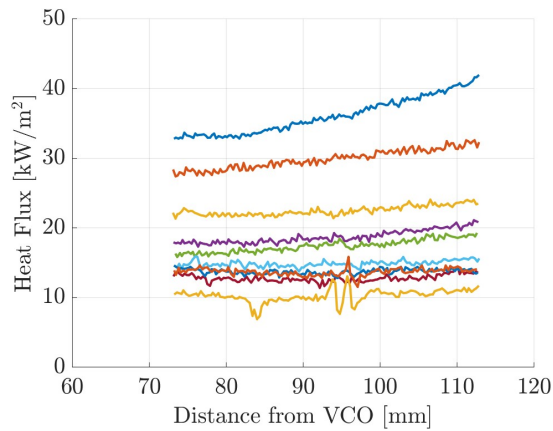
(t) 5°, Condition D



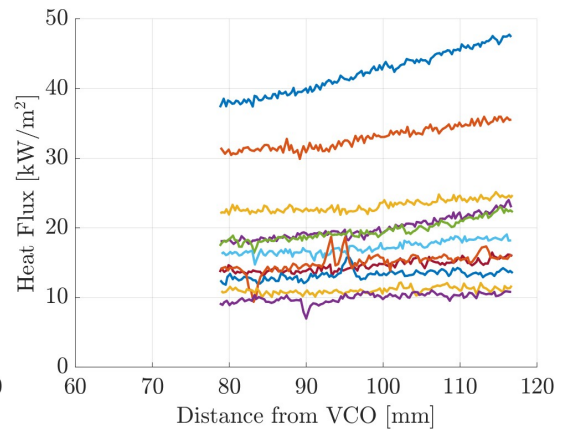
(u) 7.5°, Condition D



(v) 10°, Condition D

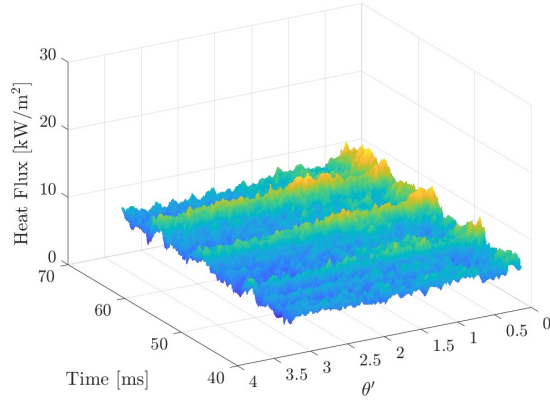


(w) 12.5°, Condition D

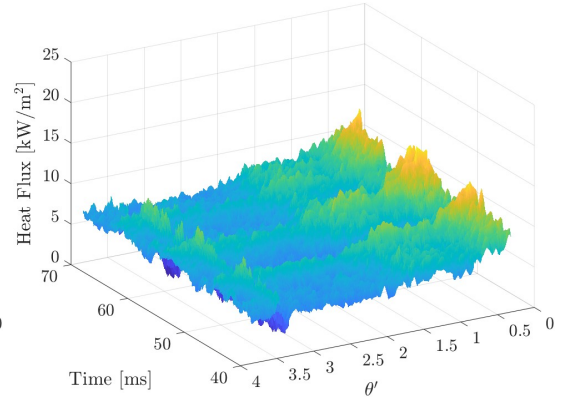


(x) 15°, Condition D

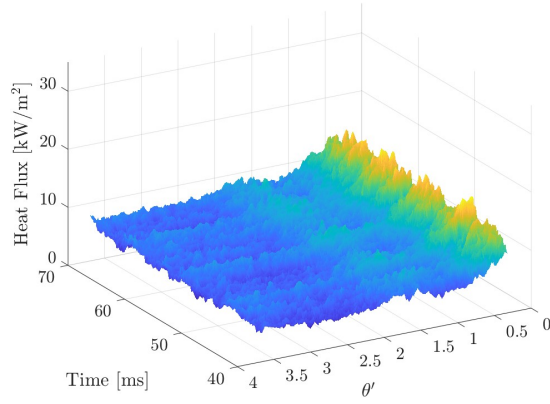
Figure D.4: (continued).



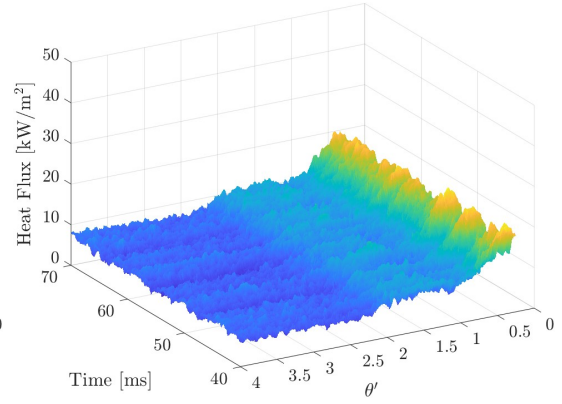
(a) 2.5°, Condition A



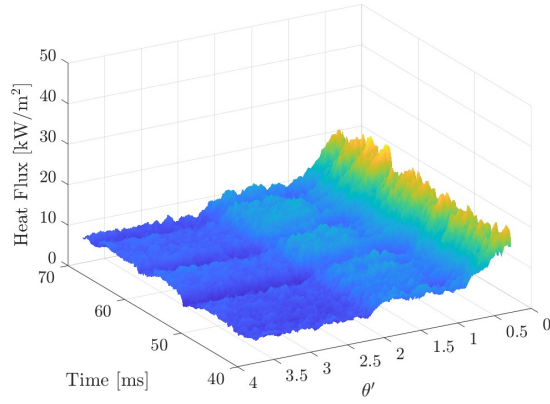
(b) 5°, Condition A



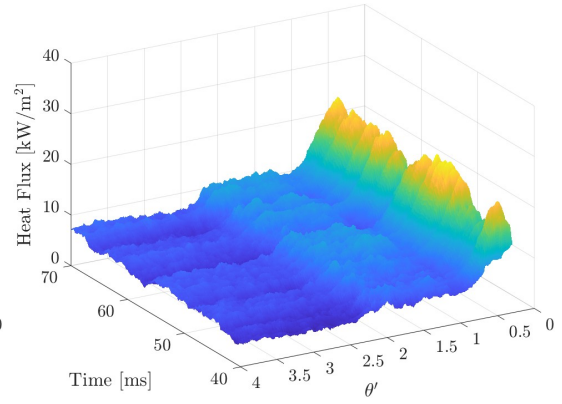
(c) 7.5°, Condition A



(d) 10°, Condition A

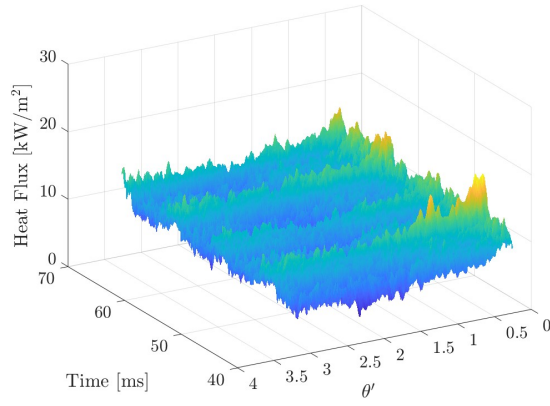


(e) 12.5°, Condition A

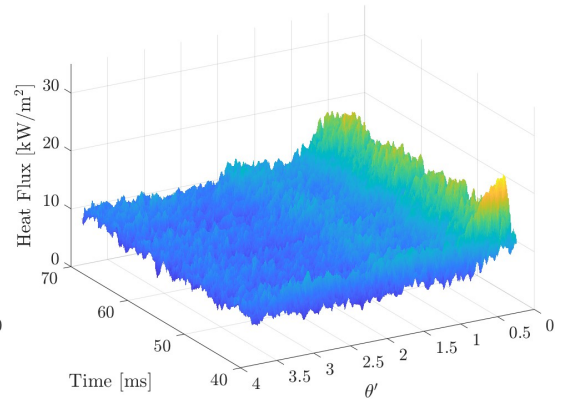


(f) 15°, Condition A

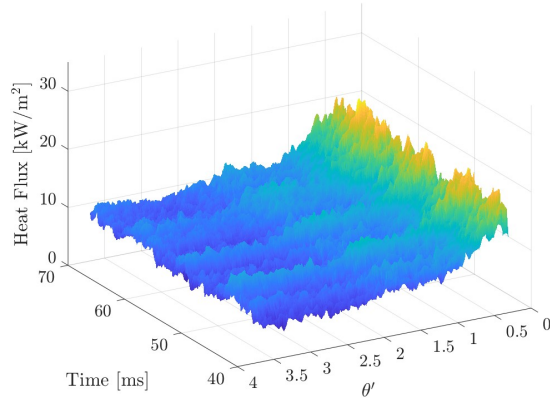
Figure D.5: Heat-flux distribution versus azimuthal location vs time (continued on the next page).



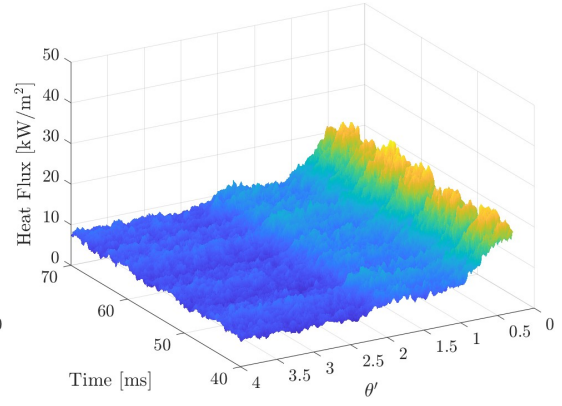
(g) 2.5°, Condition B



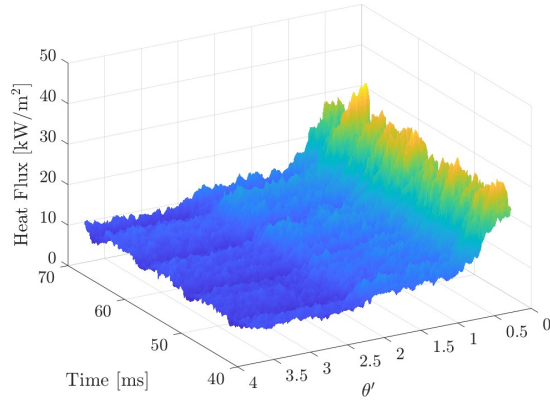
(h) 5°, Condition B



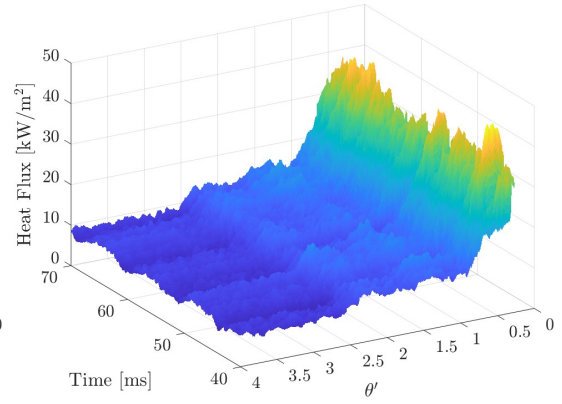
(i) 7.5°, Condition B



(j) 10°, Condition B

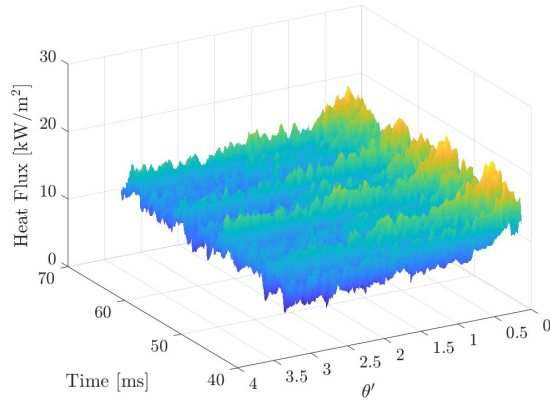


(k) 12.5°, Condition B

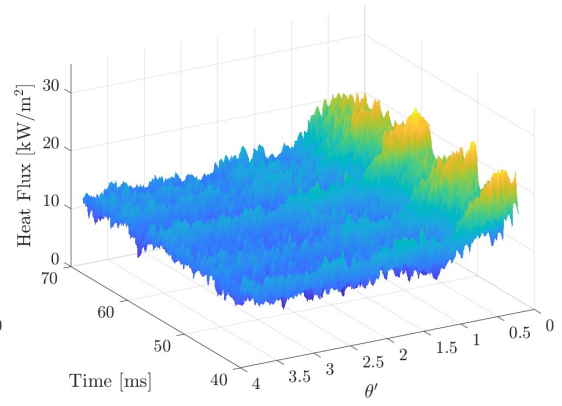


(l) 15°, Condition B

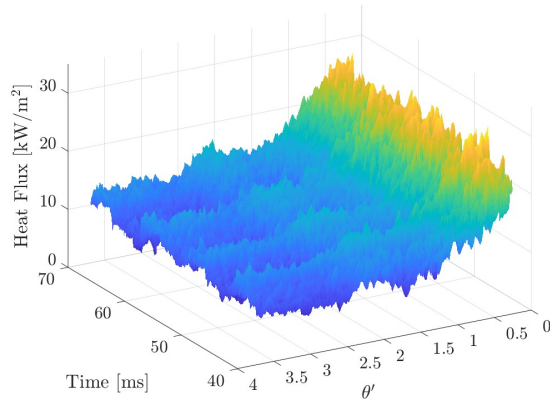
Figure D.5: (continued).



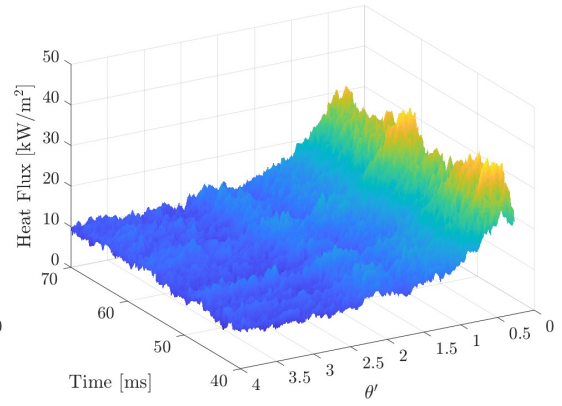
(m) 2.5°, Condition C



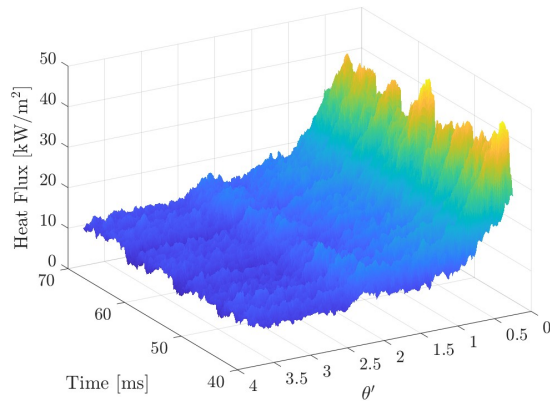
(n) 5°, Condition C



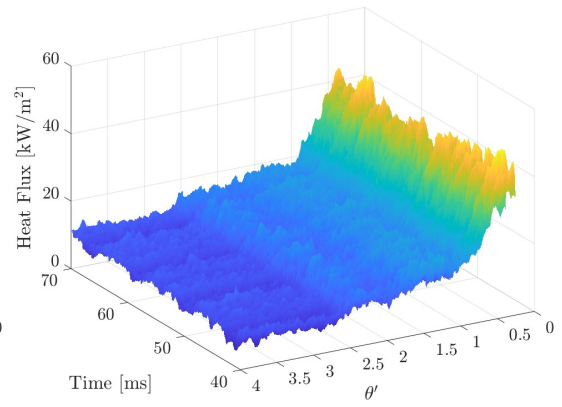
(o) 7.5°, Condition C



(p) 10°, Condition C

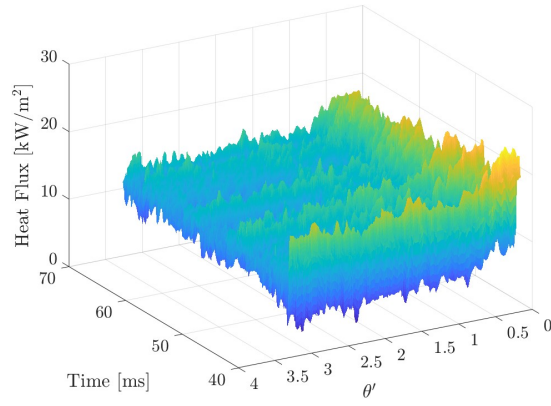


(q) 12.5°, Condition C

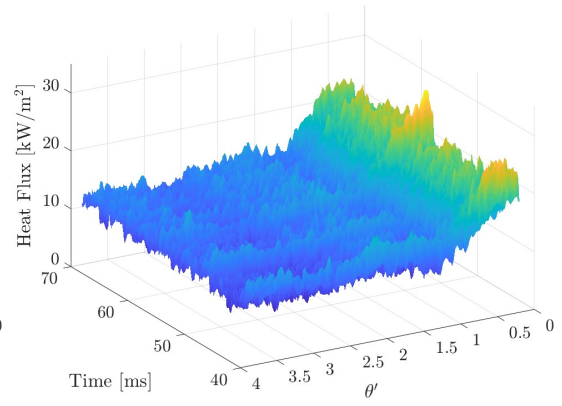


(r) 15°, Condition C

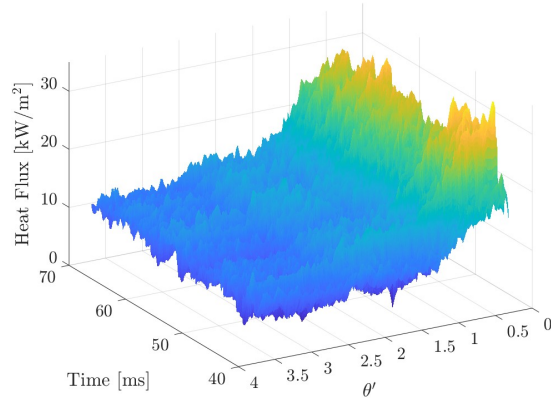
Figure D.5: (continued).



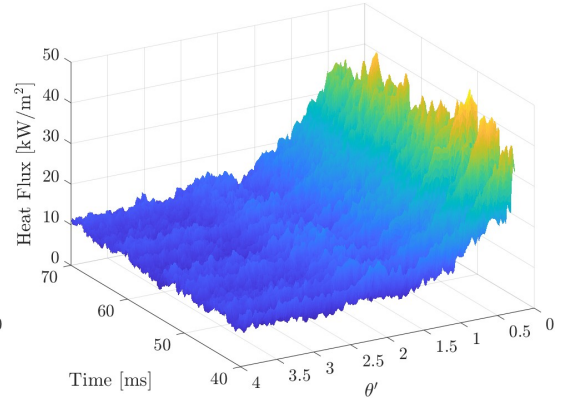
(s) 2.5°, Condition D



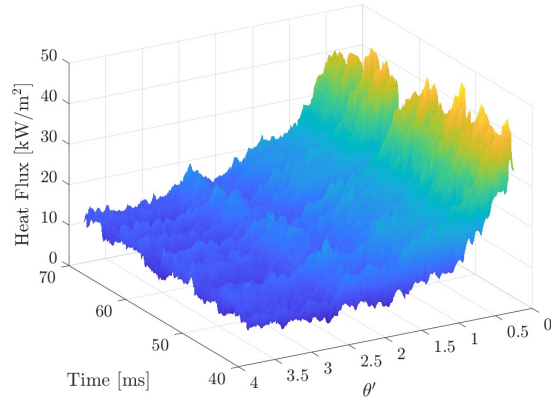
(t) 5°, Condition D



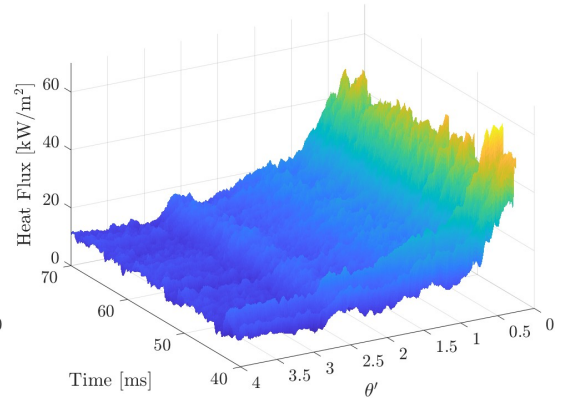
(u) 7.5°, Condition D



(v) 10°, Condition D

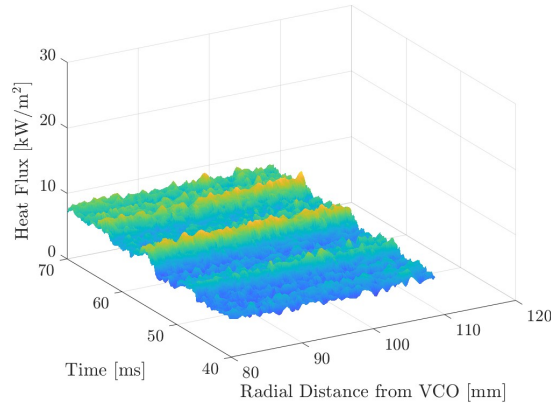


(w) 12.5°, Condition D

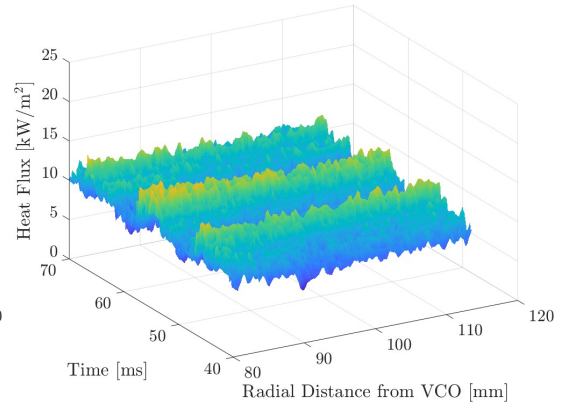


(x) 15°, Condition D

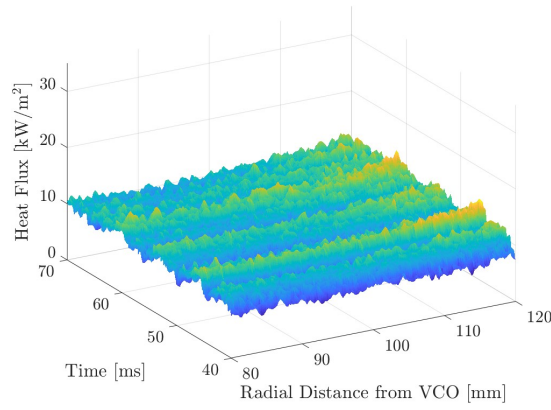
Figure D.5: (continued).



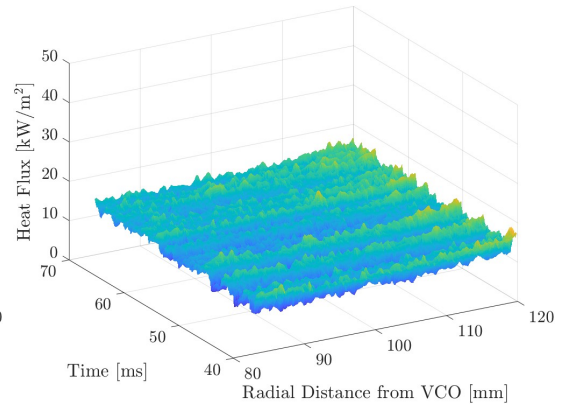
(a) 2.5°, Condition A



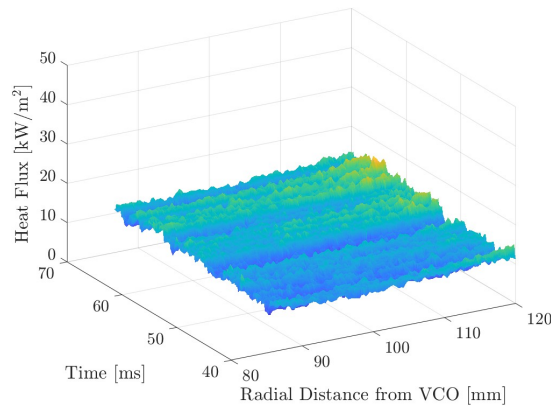
(b) 5°, Condition A



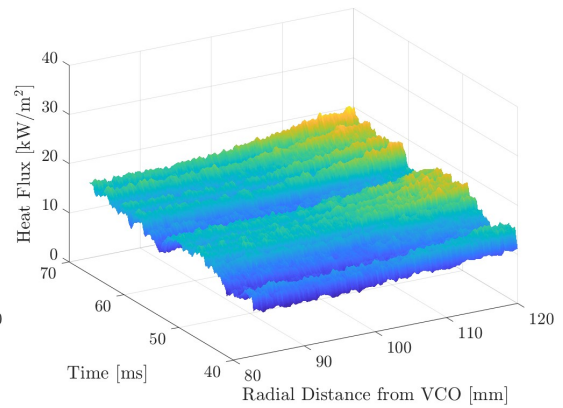
(c) 7.5°, Condition A



(d) 10°, Condition A

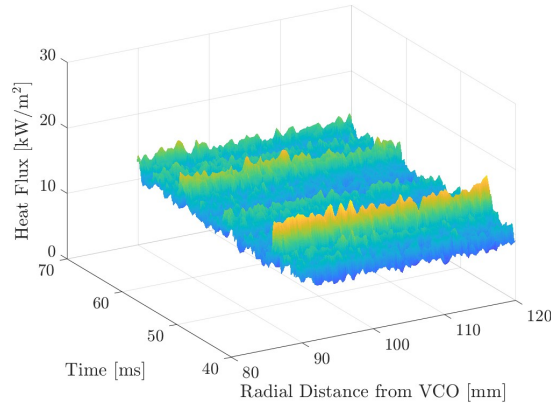


(e) 12.5°, Condition A

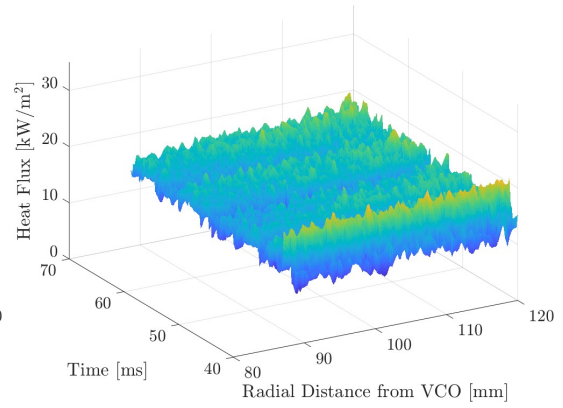


(f) 15°, Condition A

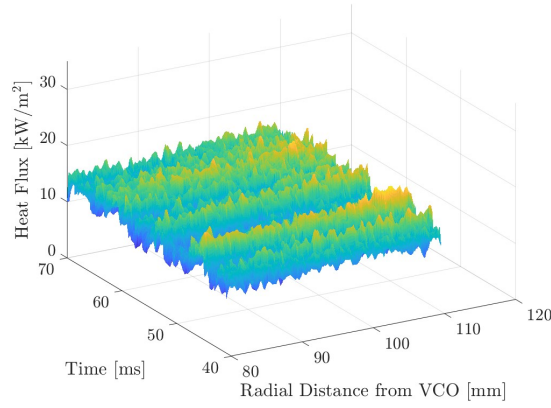
Figure D.6: Heat-flux distribution versus radial distance from VCO versus time (continued on the next page).



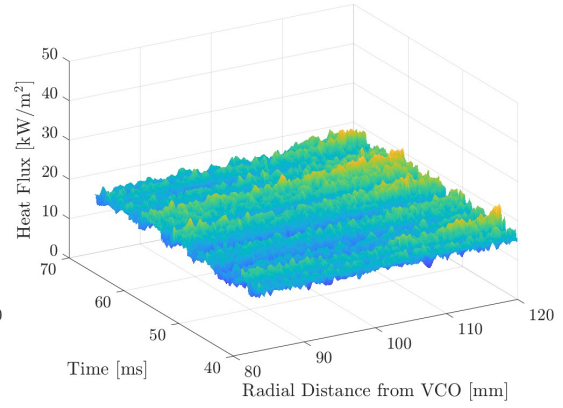
(g) 2.5°, Condition B



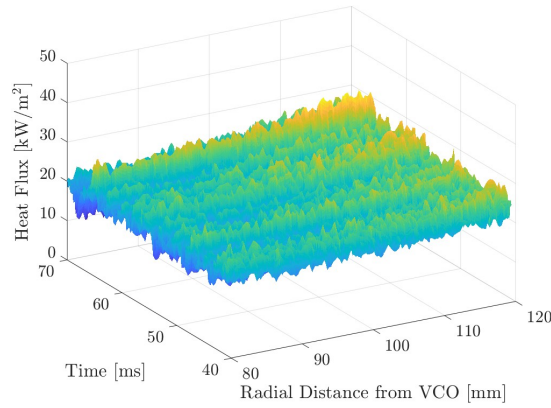
(h) 5°, Condition B



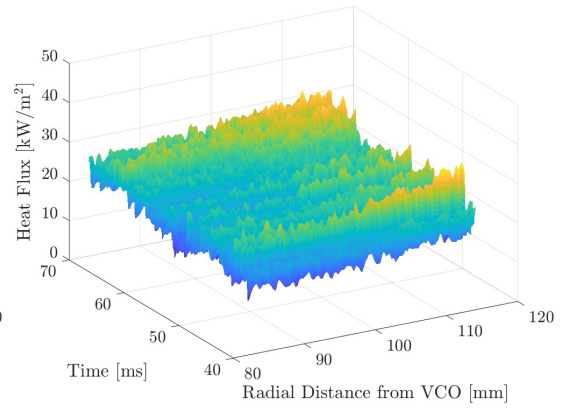
(i) 7.5°, Condition B



(j) 10°, Condition B

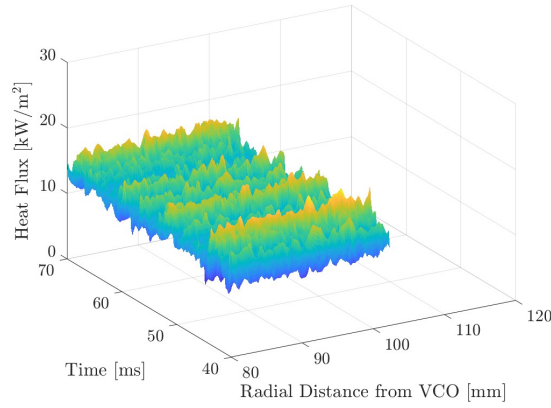


(k) 12.5°, Condition B

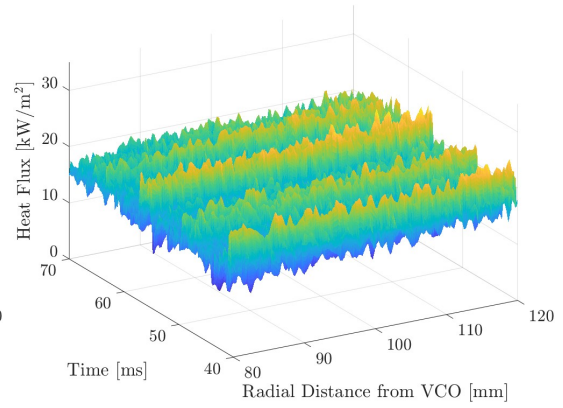


(l) 15°, Condition B

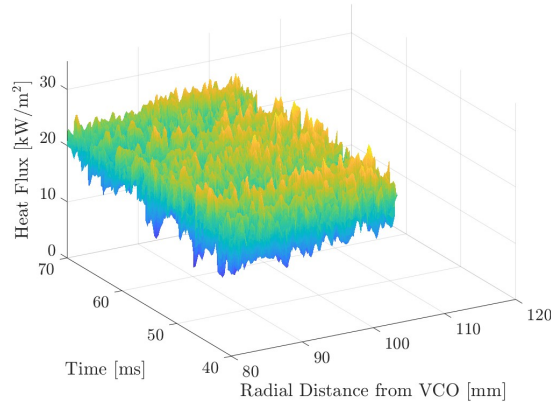
Figure D.6: (continued).



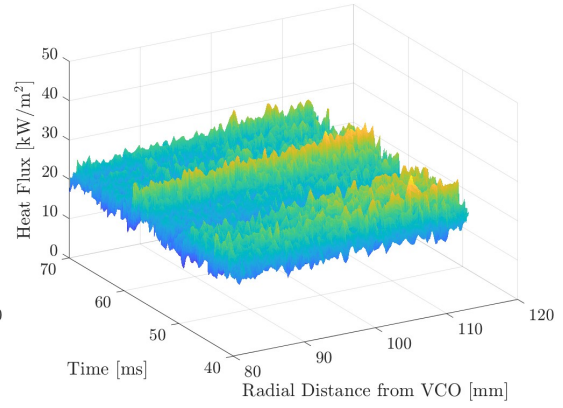
(m) 2.5°, Condition C



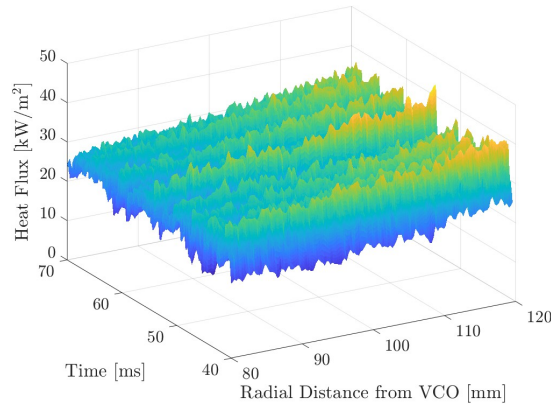
(n) 5°, Condition C



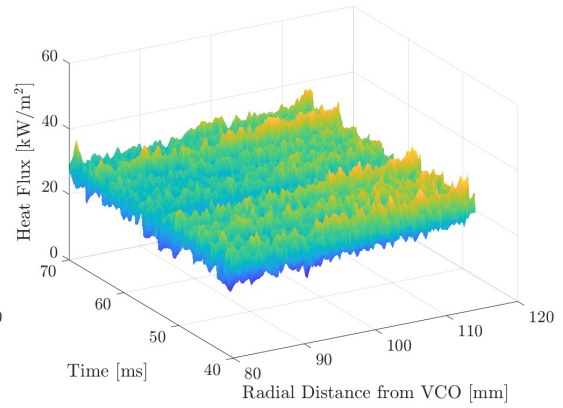
(o) 7.5°, Condition C



(p) 10°, Condition C

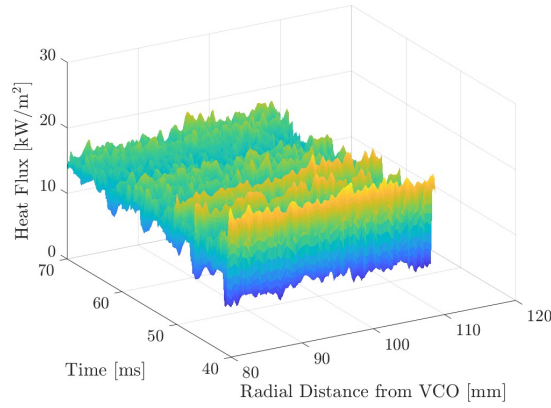


(q) 12.5°, Condition C

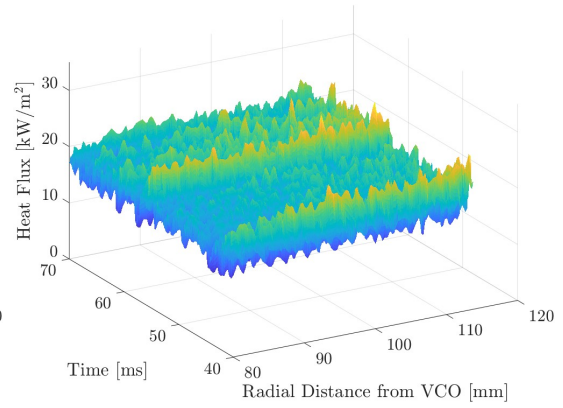


(r) 15°, Condition C

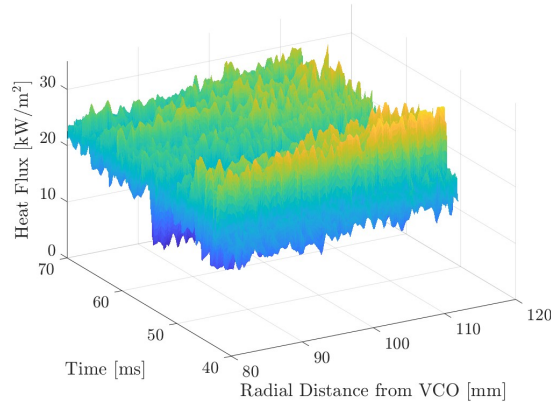
Figure D.6: (continued).



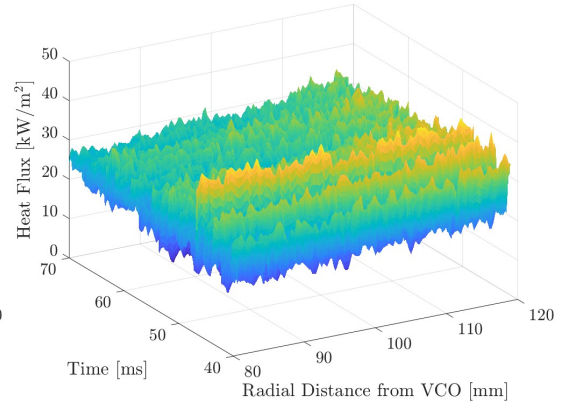
(s) 2.5°, Condition D



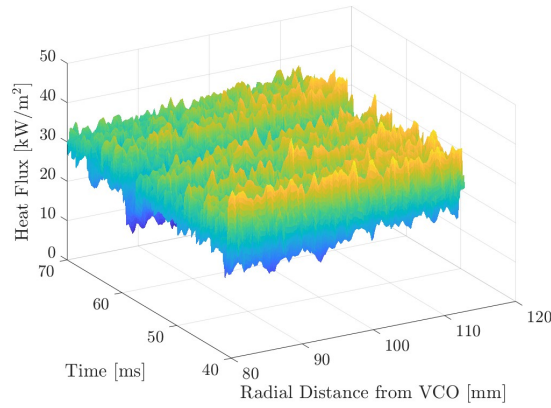
(t) 5°, Condition D



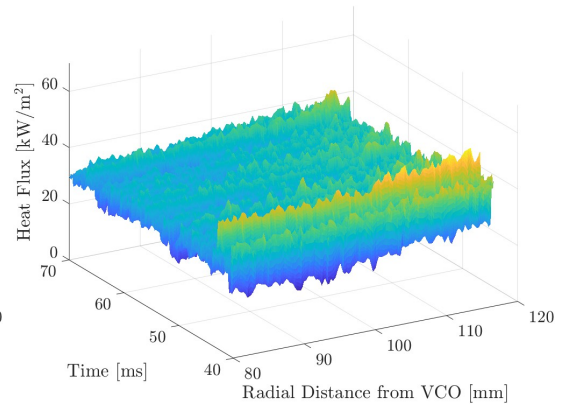
(u) 7.5°, Condition D



(v) 10°, Condition D



(w) 12.5°, Condition D



(x) 15°, Condition D

Figure D.6: (continued).

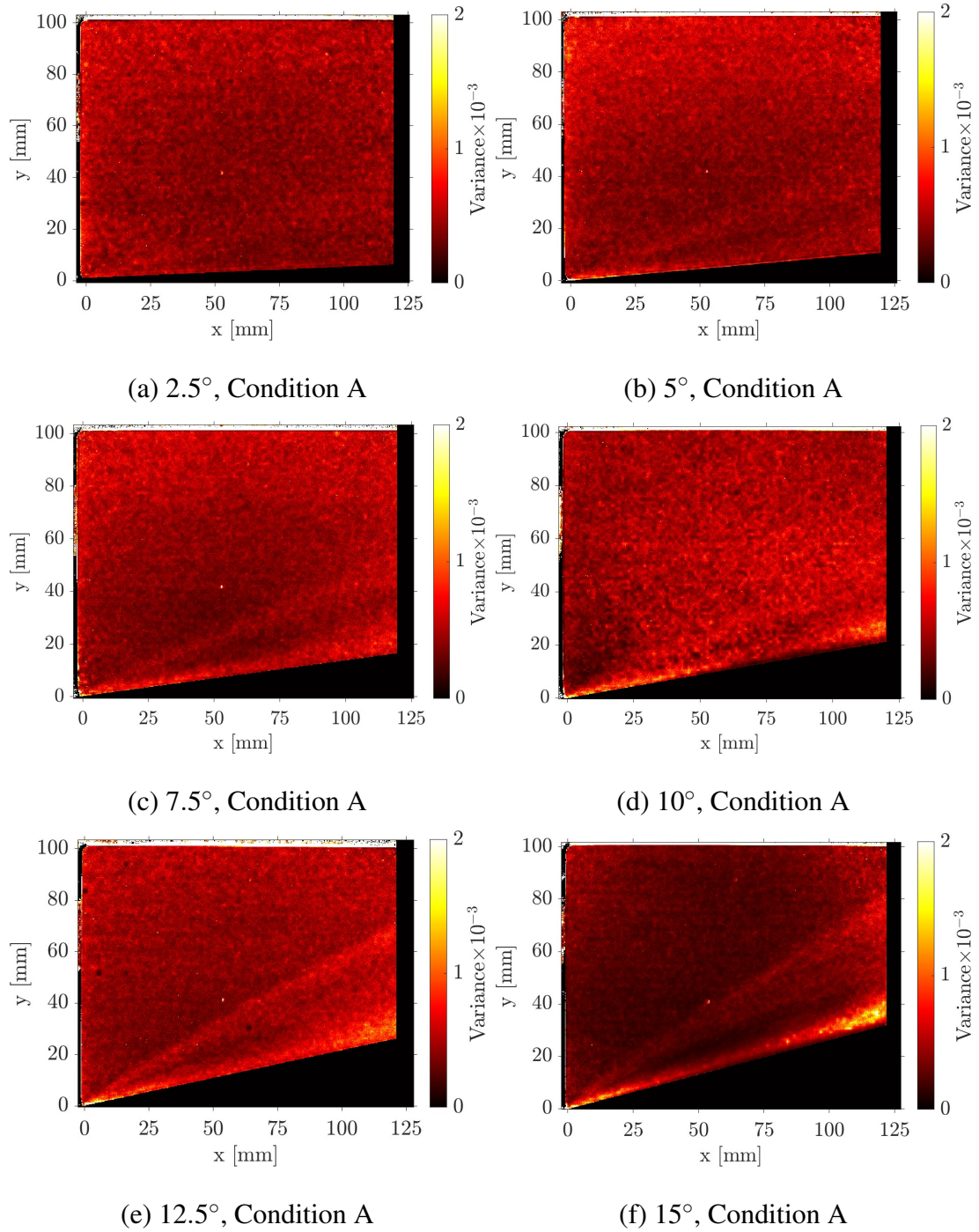


Figure D.7: Variance normalized by mean heat flux (continued on the next page).

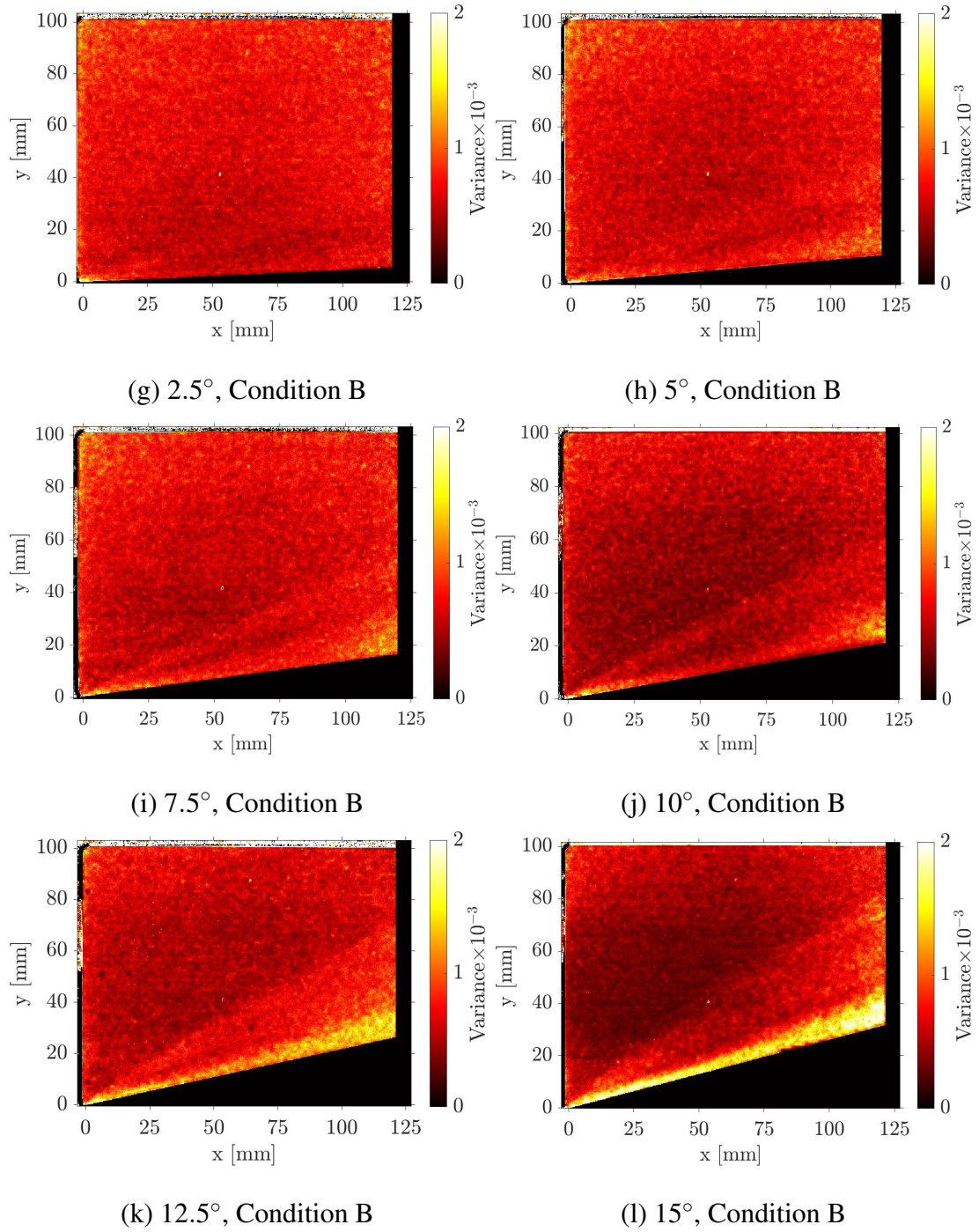


Figure D.7: (continued).

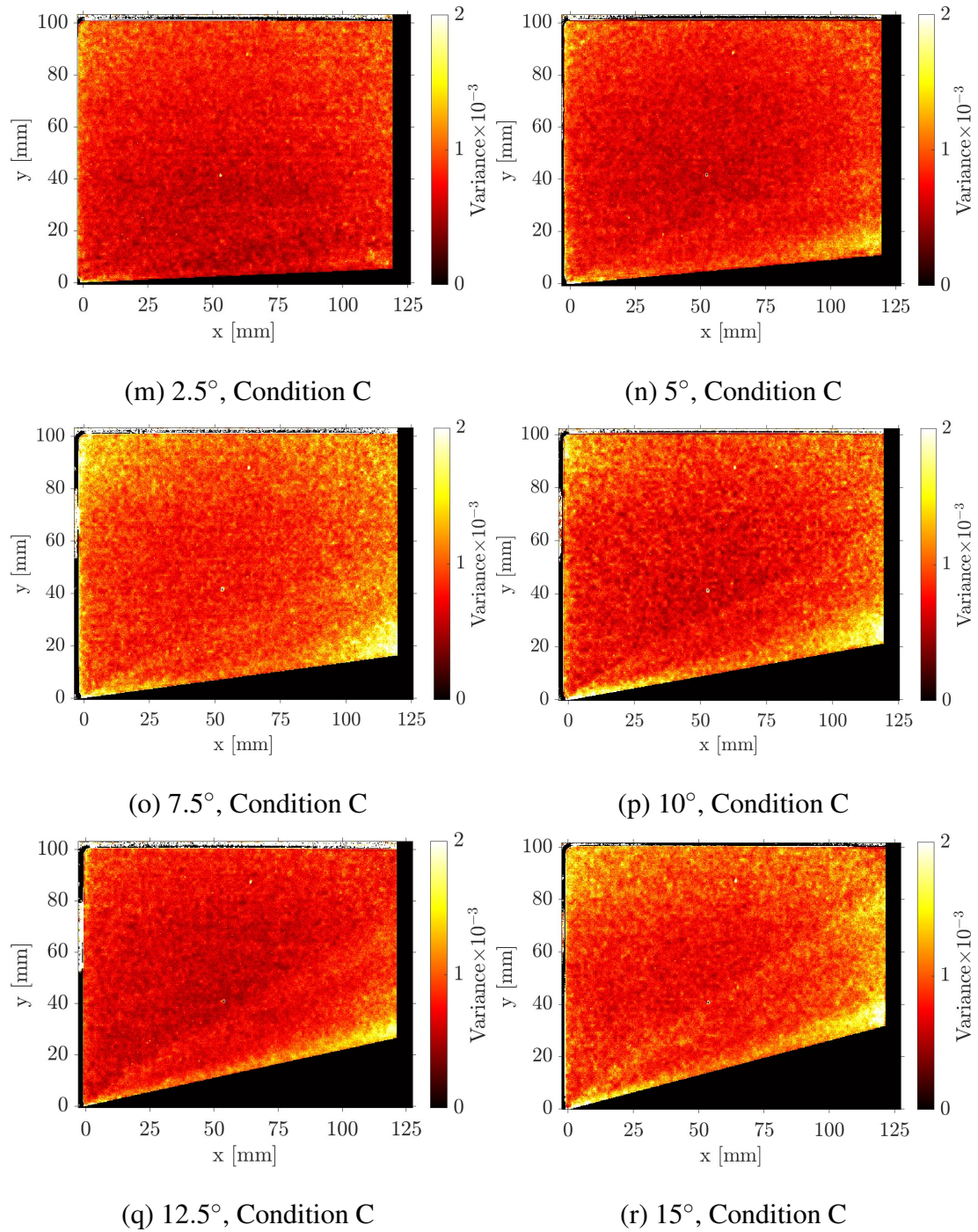


Figure D.7: (continued).

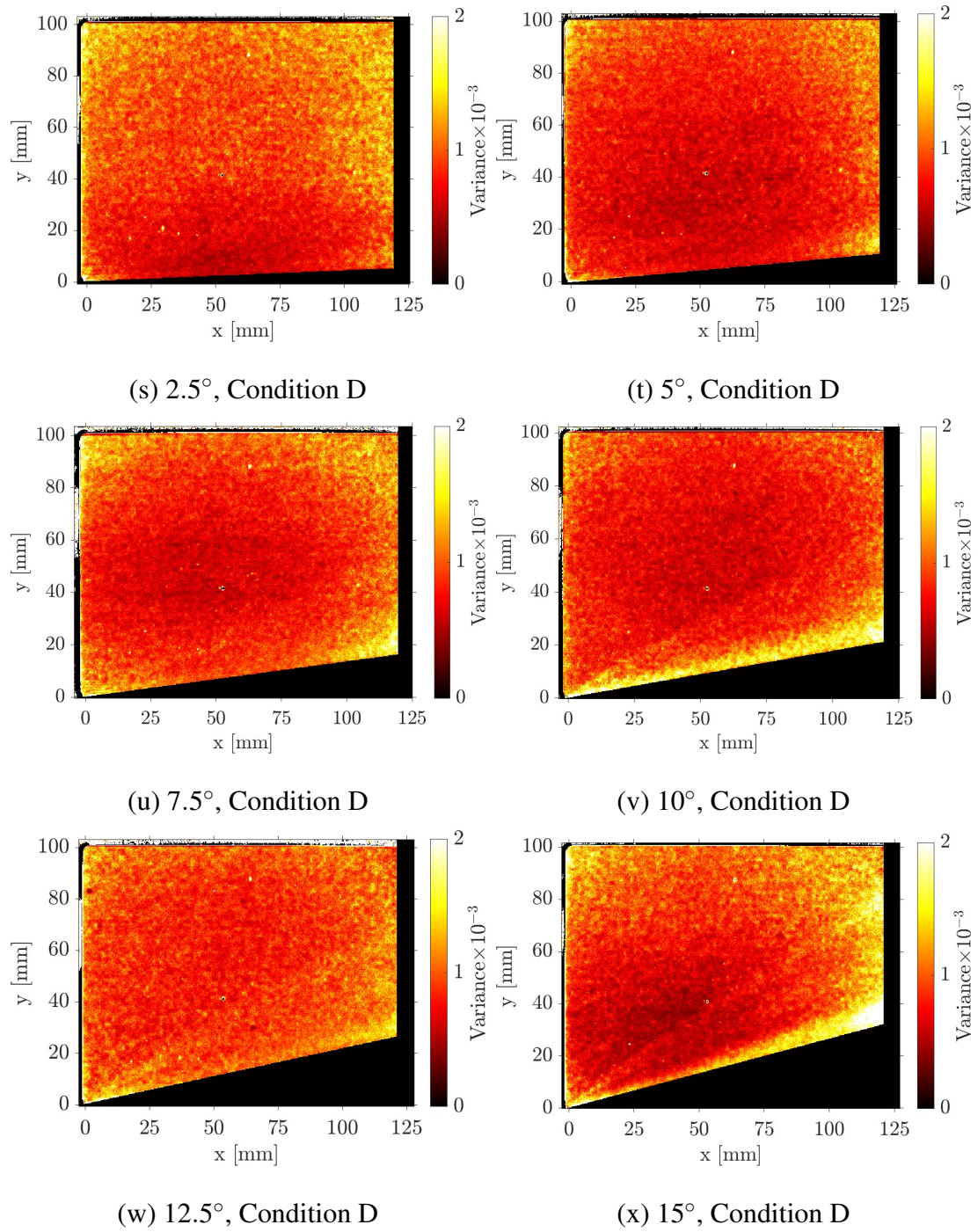
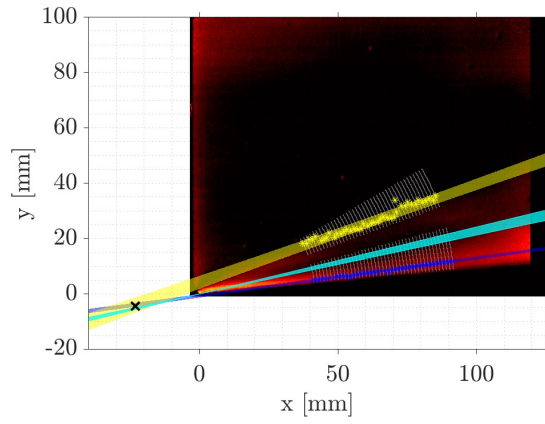
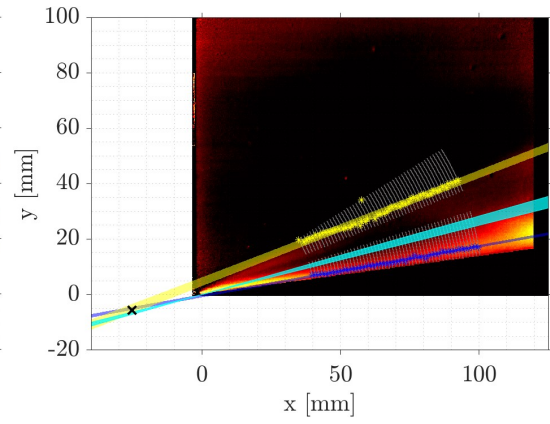


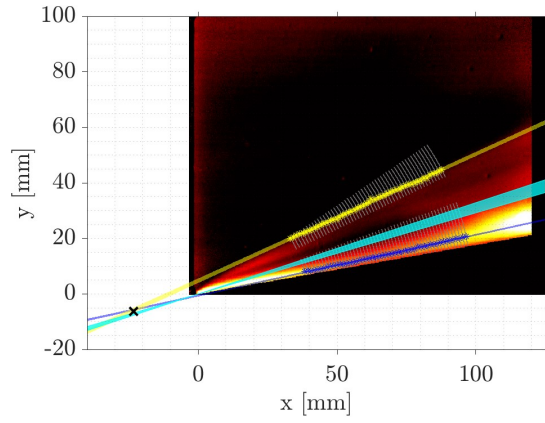
Figure D.7: (continued).



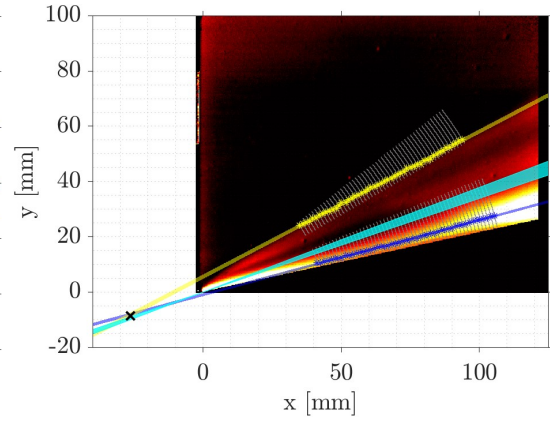
(a) 5° , Condition A



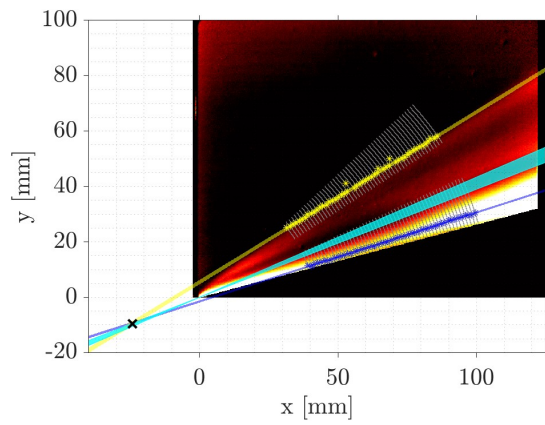
(b) 7.5° , Condition A



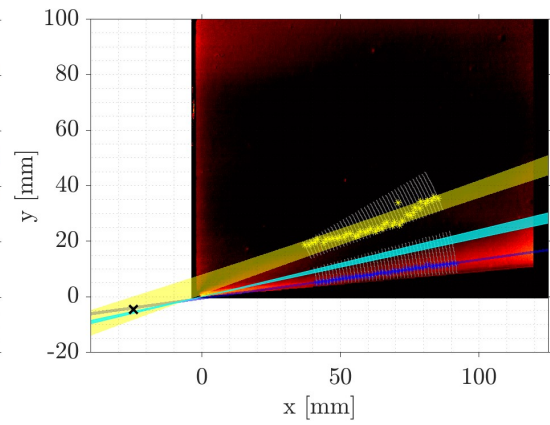
(c) 10° , Condition A



(d) 12.5° , Condition A

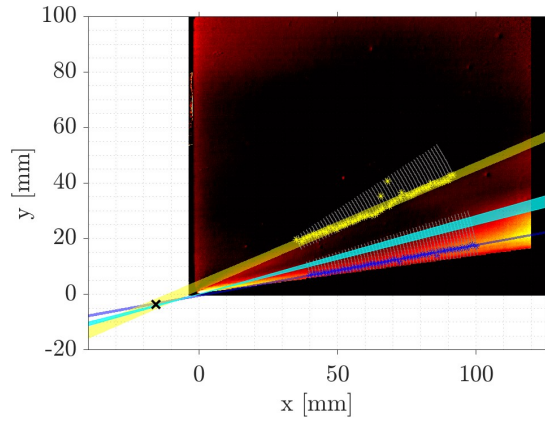


(e) 15° , Condition A

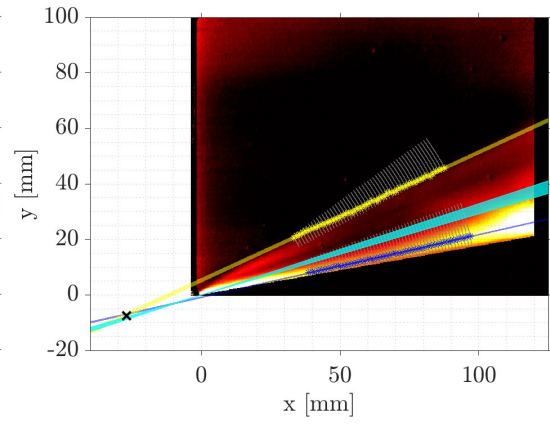


(f) 5° , Condition B

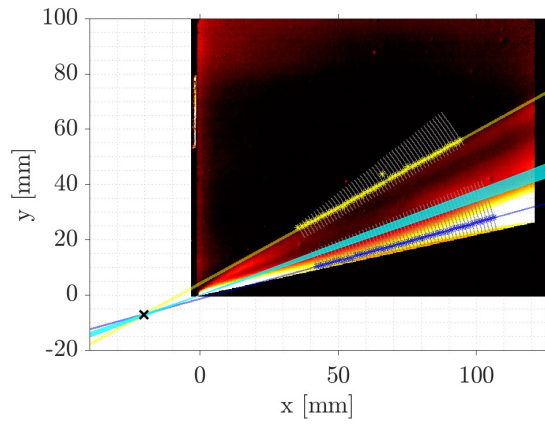
Figure D.8: VCO search methodology visualization (continued on the next page).



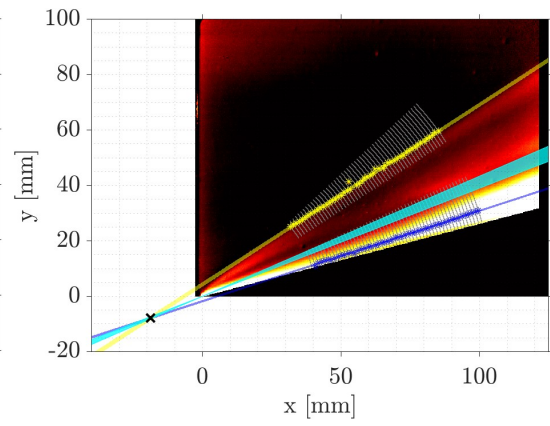
(g) 7.5° , Condition B



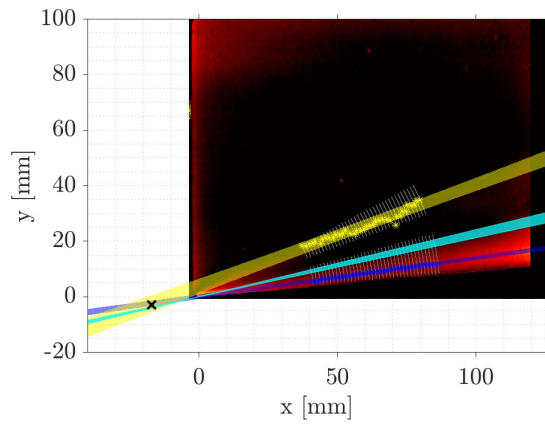
(h) 10° , Condition B



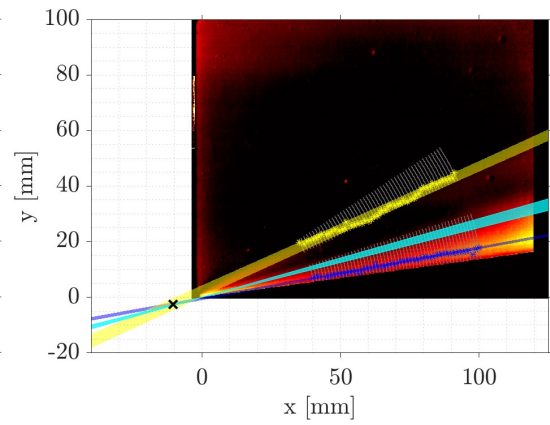
(i) 12.5° , Condition B



(j) 15° , Condition B

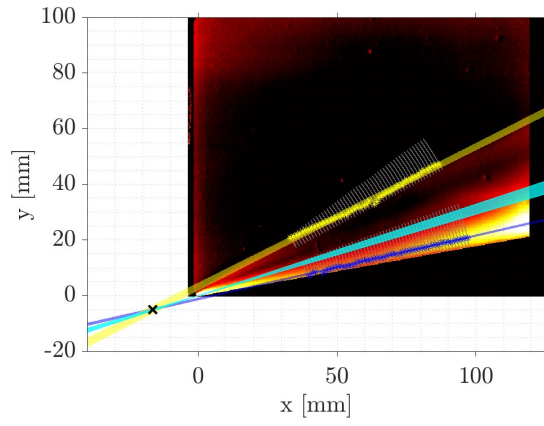


(k) 5° , Condition C

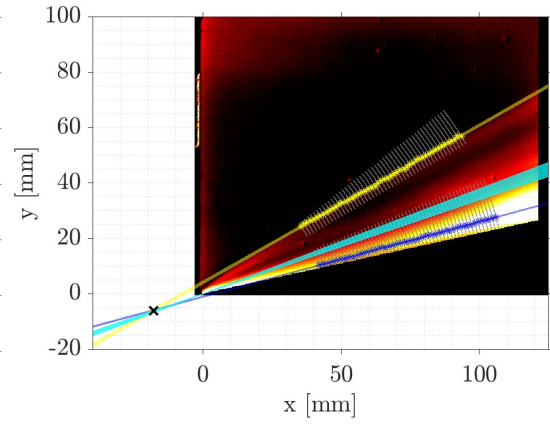


(l) 7.5° , Condition C

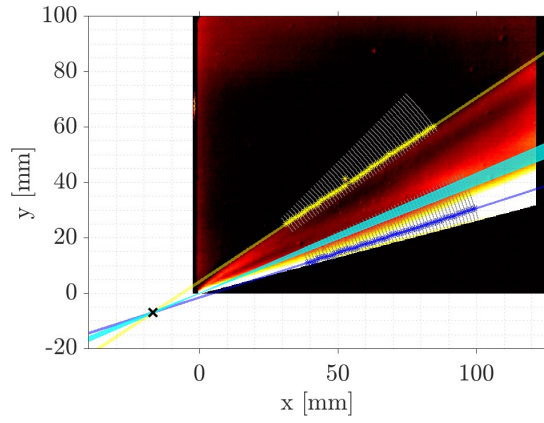
Figure D.8: (continued).



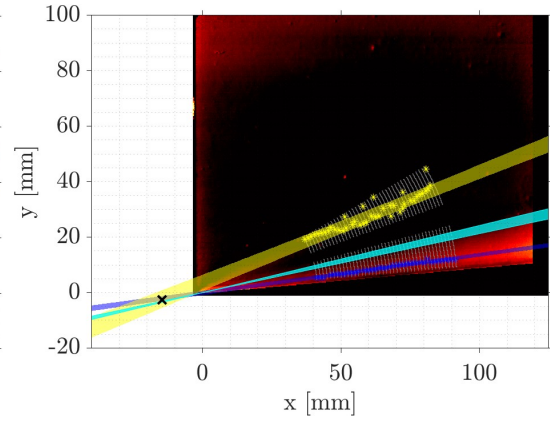
(m) 10° , Condition C



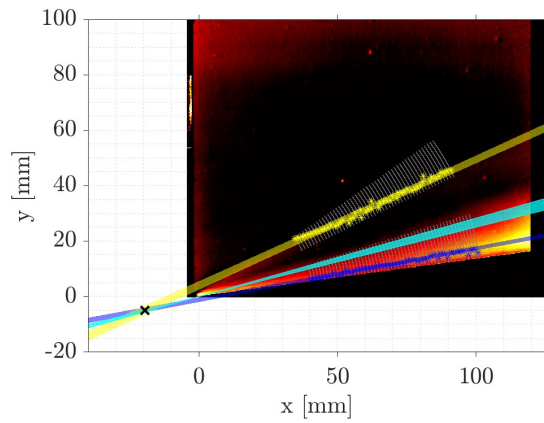
(n) 12.5° , Condition C



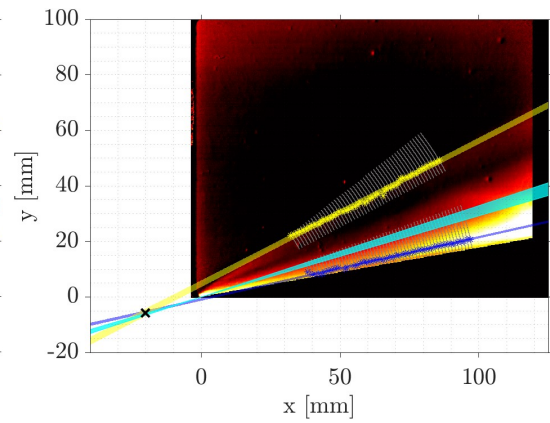
(o) 15° , Condition C



(p) 5° , Condition D

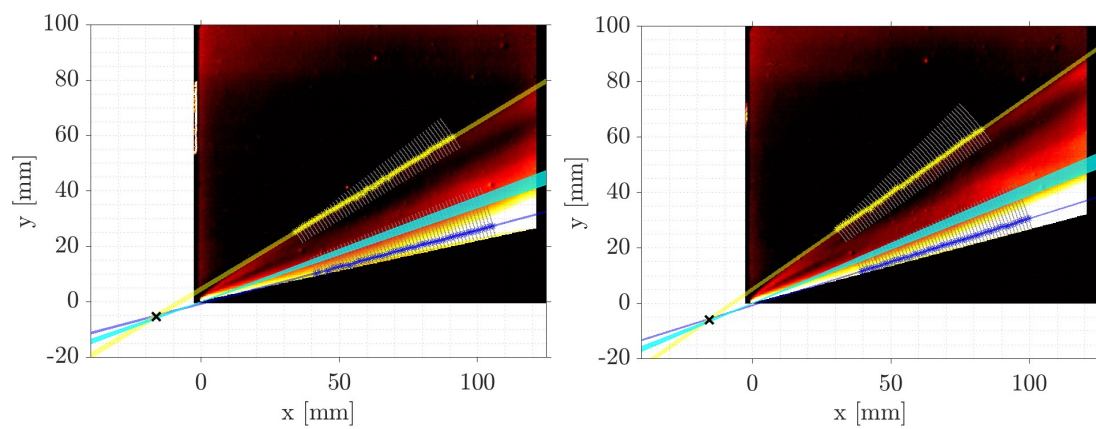


(q) 7.5° , Condition D



(r) 10° , Condition D

Figure D.8: (continued).



(s) 12.5° , Condition D

(t) 15° , Condition D

Figure D.8: (continued).

D.2 High-speed schlieren

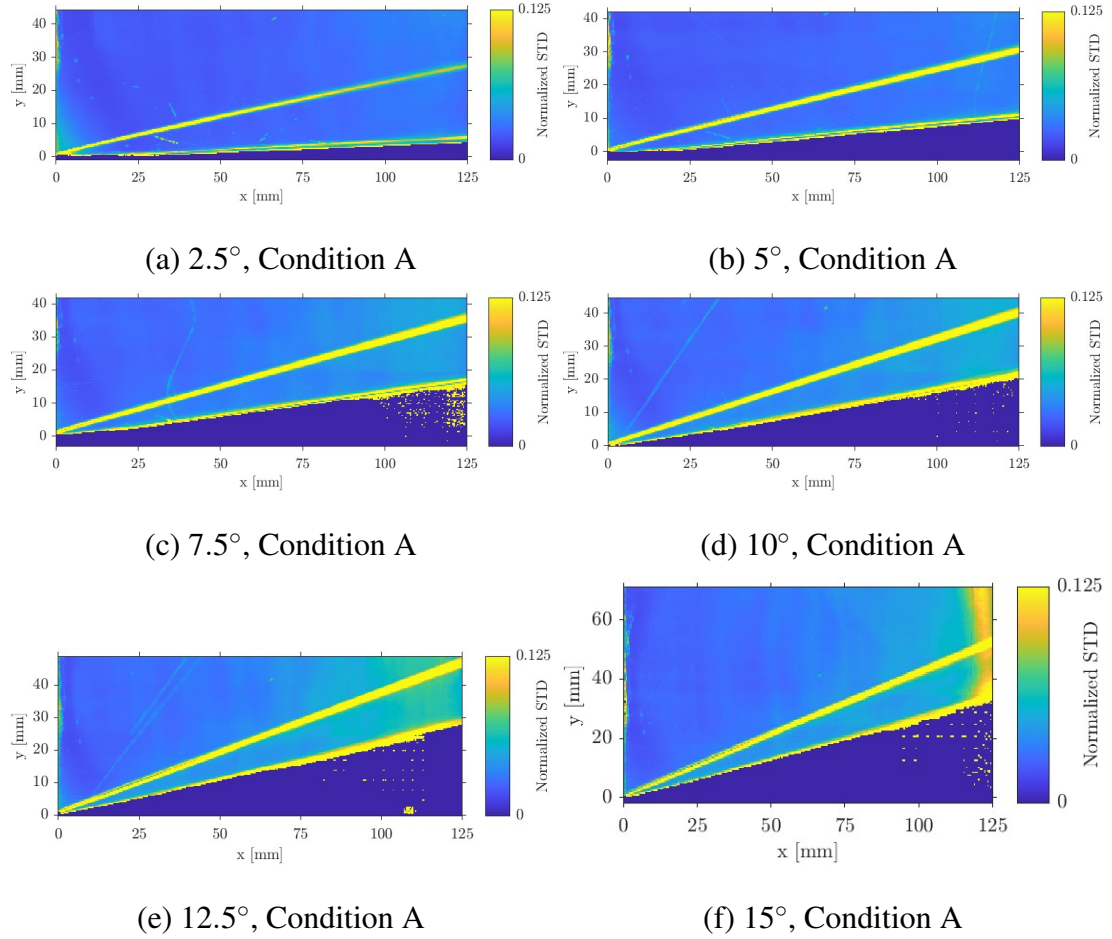


Figure D.9: Normalized schlieren standard deviation for each fin angle (continued on the next page).

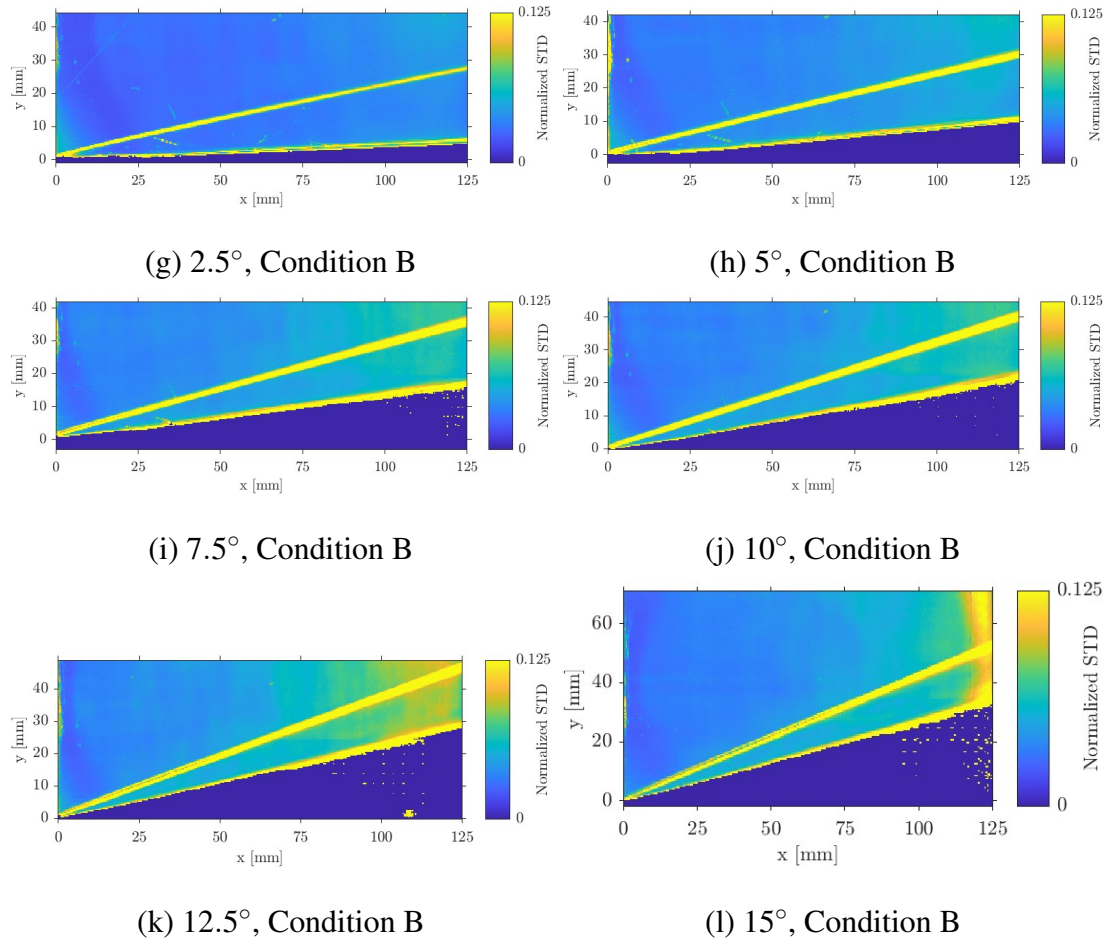


Figure D.9: (continued).

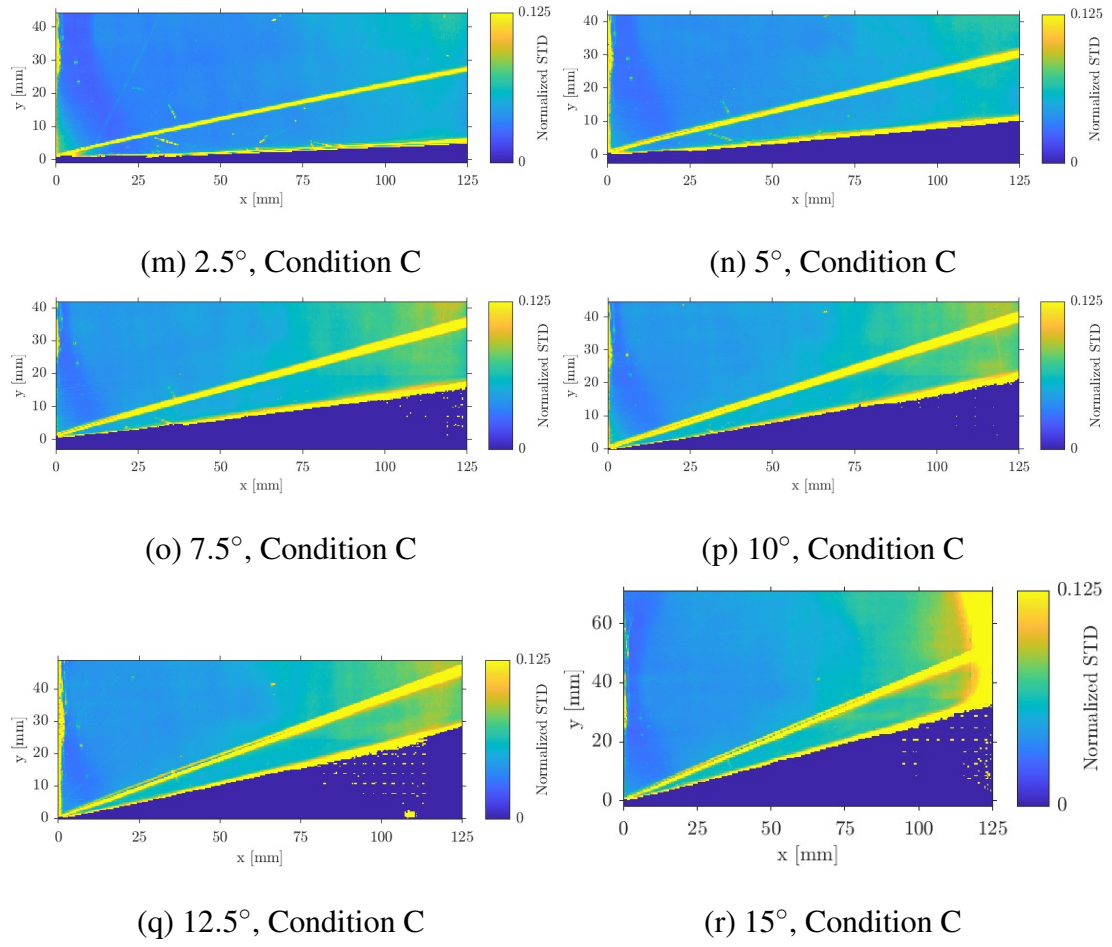


Figure D.9: (continued).

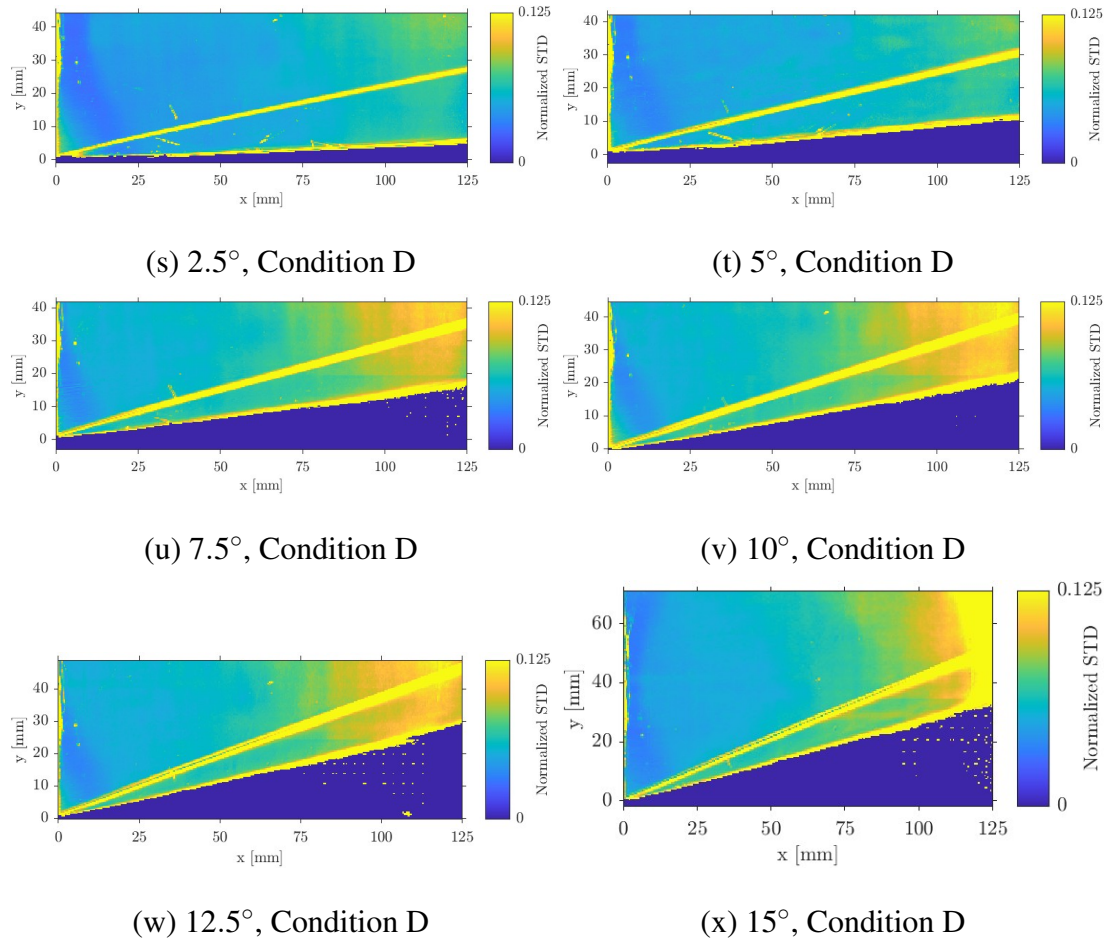


Figure D.9: (continued).

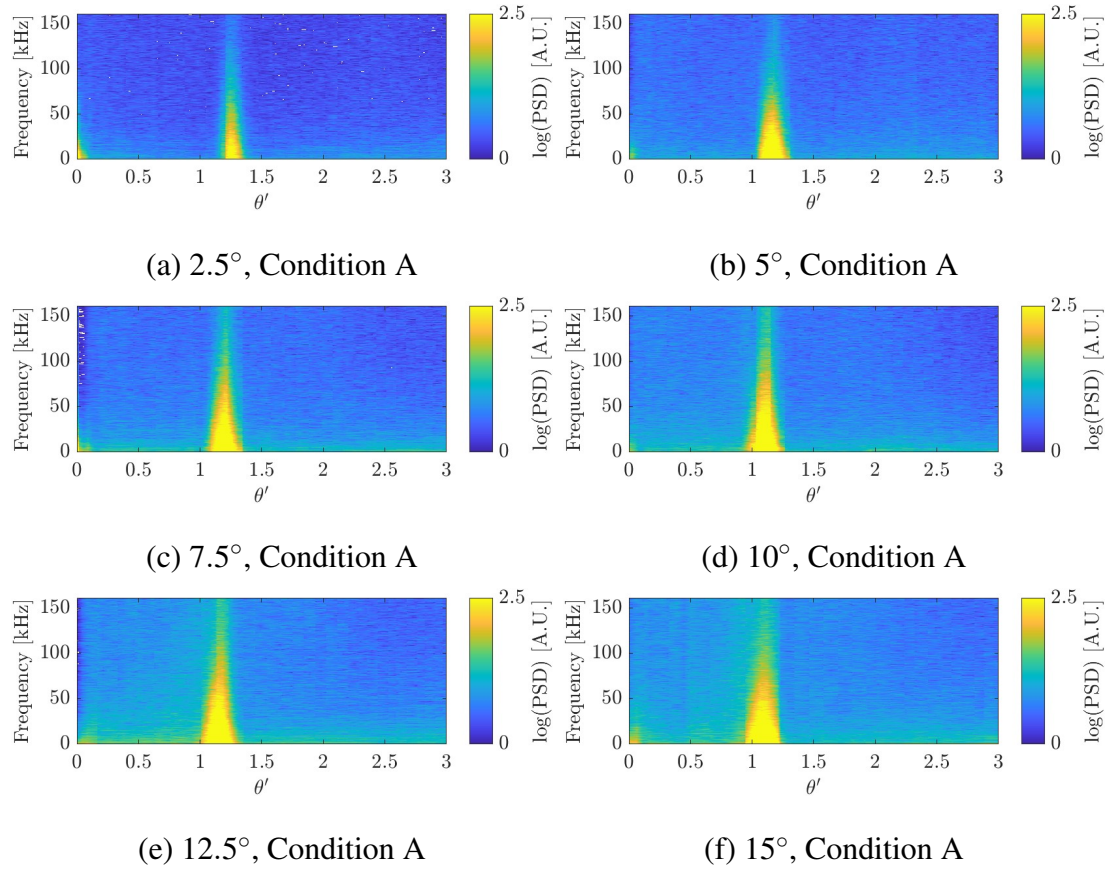
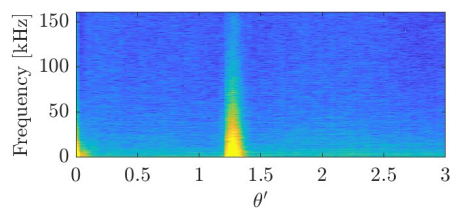
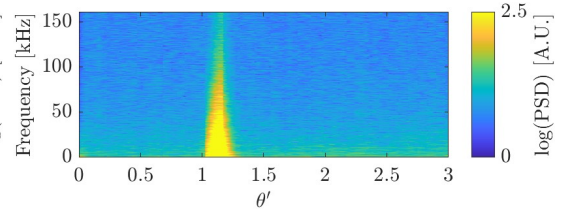


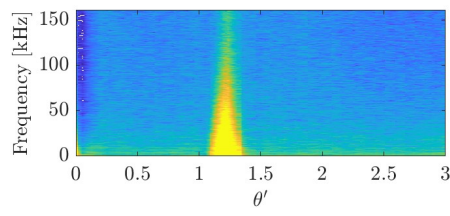
Figure D.10: Power spectral density analysis along a circular arc for each fin angle (continued on the next page).



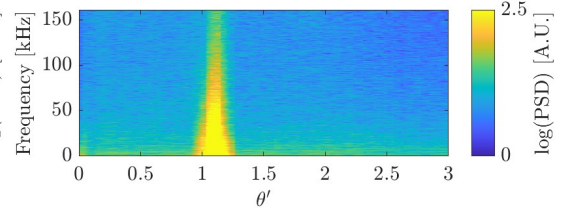
(g) 2.5° , Condition B



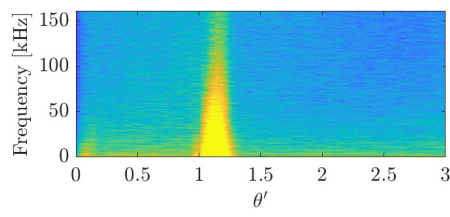
(h) 5° , Condition B



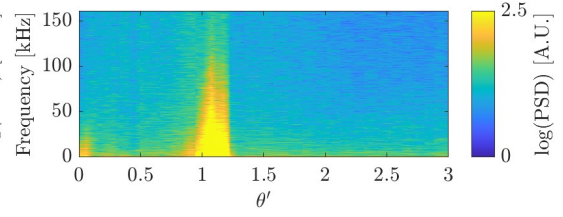
(i) 7.5° , Condition B



(j) 10° , Condition B



(k) 12.5° , Condition B



(l) 15° , Condition B

Figure D.10: (continued).

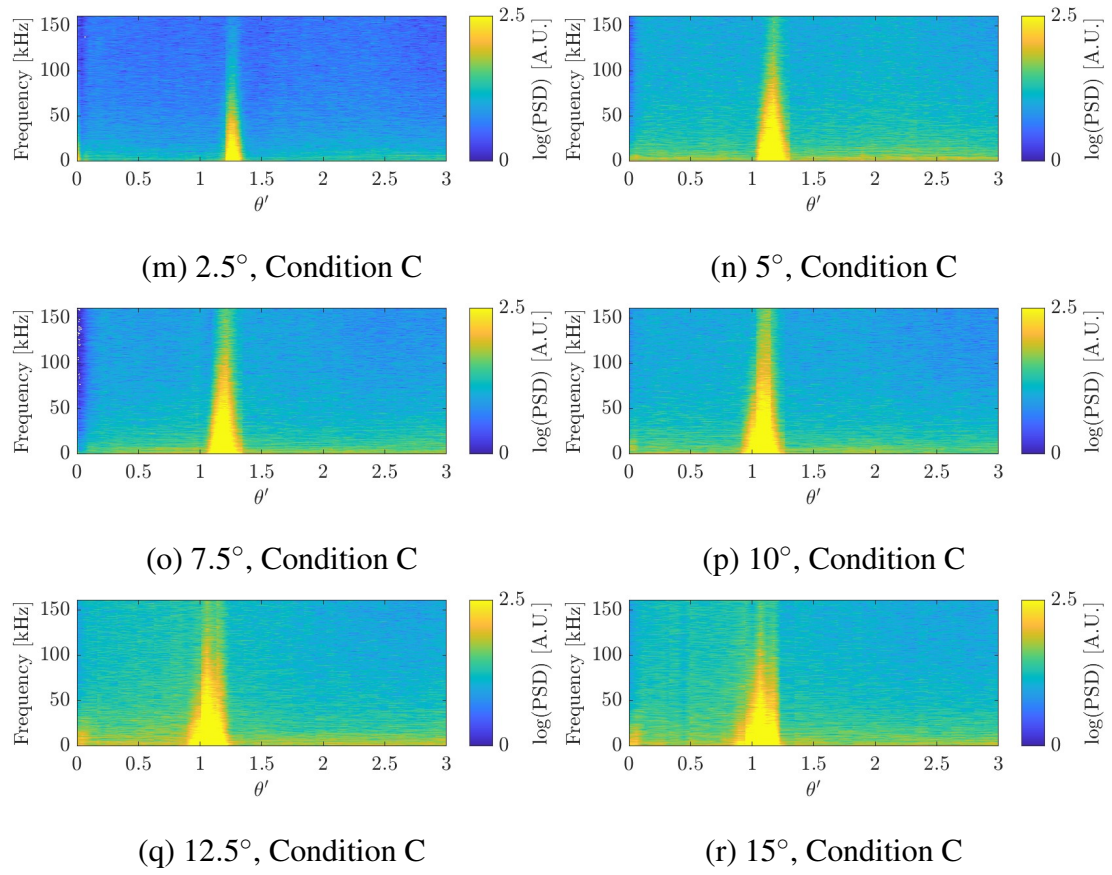


Figure D.10: (continued).

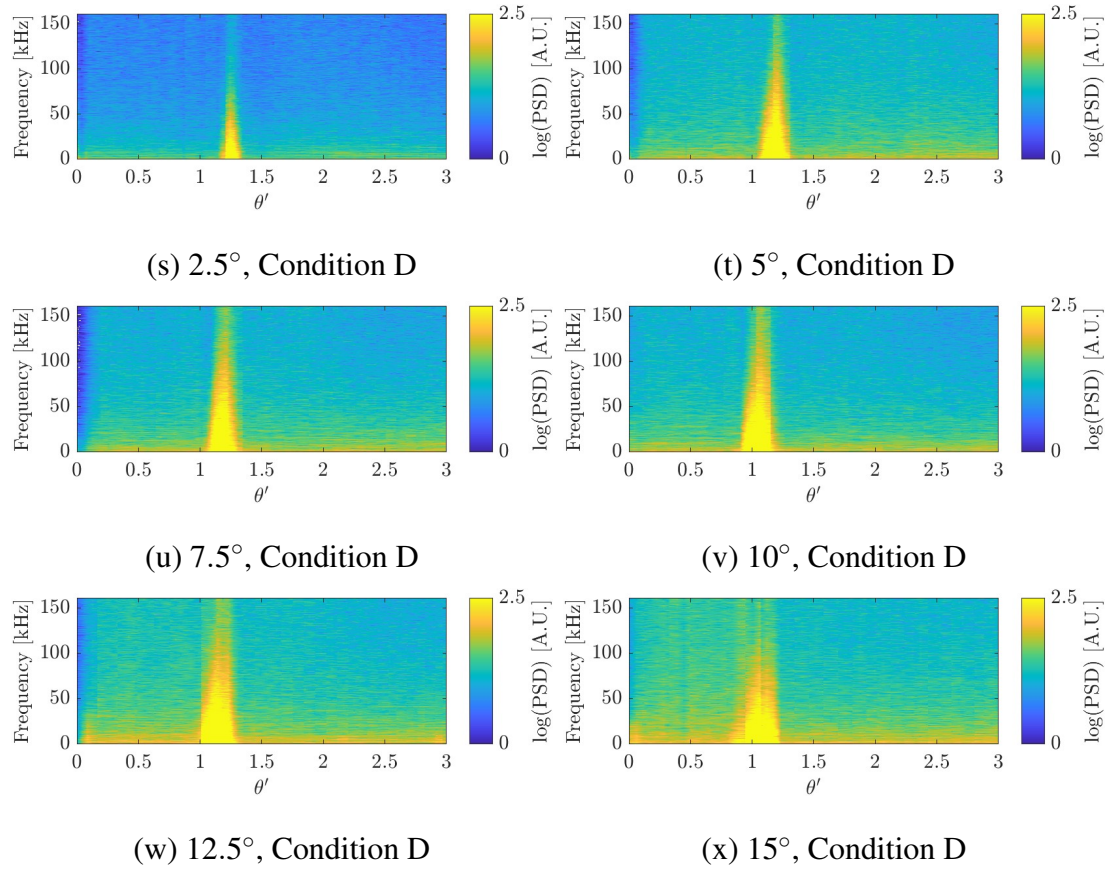


Figure D.10: (continued).

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