Proceedings of AVT-200 Specialists' Meeting on Hypersonic Laminar-Turbulent Transition, San Diego, CA. April 16-19, 2012.

Time Resolved Heat-Flux Measurements on a CEV Candidate Shape at High Enthalpy

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ABSTRACT

An experimental study of hypersonic flow over a candidate model for the CEV reentry capsule was conducted with the aim of observing the heat-flux at high enthalpy in T5, Caltech's free-piston driven reflected shock tunnel ([1–6]). To supplement these internal reports additional data processing (the creation of heat-flux movies) is presented in this work. In total, there were six parts to the CEV study; heat-flux movies are made from the data reported in four of them ([2], [3], [5], [6]). This report describes the phenomena observed and the conclusions that are drawn from the heat-flux movies of hypervelocity flow over a CEV candidate shape.

1.0 INTRODUCTION

Following the retirement of the Space Shuttle, NASA focused on developing a replacement, the Crew Exploration Vehicle (CEV). The CEV is an Apollo-like capsule, capable of return from low Earth orbit, lunar, and interplanetary missions. There is a window of time during reentry where the forebody is subjected to extreme heat-flux and skin friction. As a result, one of the main design concerns of the CEV is its thermal protection system (TPS). The TPS protects the CEV's crew, cargo, and instrumentation during periods of extreme aerodynamic heating. For vehicles in hypersonic flight, transition to turbulence in the boundary layer leads to large increases in heat-flux and skin friction, which influences the design (primarily mass considerations [7]) of the TPS. Therefore, transition prediction in the boundary layer is important to overall mission design.

As discussed in [8], laminar-turbulent transition in hypersonic boundary layers is not fully understood, wich led the CEV TPS to be designed conservatively assuming a fully turbulent boundary layer [9]. Two transition mechanisms are the crossflow instability and surface roughness [10–12]. Possible sources of roughness elements include misaligned TPS tiles, as well as spallation and ablation caused by the extreme surface temperatures present during reentry ([9]). Surface roughnesses fall into two categories ([8]): discrete, isolated roughness (such as the gaps in the TPS tiling), and distributed roughness (such as that caused by ablation). Roughness elements can be simulated through the use of "trips" on the surface of the experimental model. Surface roughness tends to promote transition to a degree that is proportional to the height of the roughness element ([8], [13]). Additional reviews on transition data for capsules and planetary probes can be found in [14] and [15].

This report discusses the creation and analysis of movies produced from heat-flux studies performed on a candidate model for the CEV reentry capsule at high enthalpy. In total, there were six parts to the CEV study ([1–6]); movies are made from the data of four of them ([2], [3], [5], [6]). The movies show the evolution of the heat-flux on the surface of the model during each run. An additional analysis of the data from [2], [3], and [6] can be found in [16].

In Part II of the experiments, the CEV model was tested at varying angles of attack, reservoir pressures and reservoir enthalpies. For Part III, the tests were performed at a fixed angle of attack (28°), and the reservoir pressure and reservoir enthalpy were varied over a range similar to Part II. Part V of the experiments focused on reduced chemistry experiments. For some runs, a mixture of Argon, Neon, and Oxygen was used to create a gas with the same molecular weight as air, but without Nitrogen chemistry; in addition, an Argon-Neon mixture was used to create a gas with the same molecular weight as air but without all chemical reactions. For the tests in Part VI, a trip insert with 25 0.05-inch square "pizza box" roughness elements was added to the CEV model to promote transition; the trip was located 0.345 inches below the geometric center of the CEV model. The height of the trips varied (0, 0.007, 0.010, and 0.015 in).

All experiments discussed in this report were conducted in the T5 hypervelocity shock tunnel at the California Institute of Technology; for a detailed description of the facility, please see [2]. Also, [2] contains a detailed description of the data acquisition system. The design of the thermocouples used is described in [17].

2.0 MODEL DESCRIPTION

The shape of the model for the experiments was provided by Dr. Joseph Olejniczak. Its size was determined by the exit diameter of the T5 nozzle, as the model was to be as large as possible without interacting with the expansion wave coming from the nozzle exit. A model diameter of 7 in was selected.

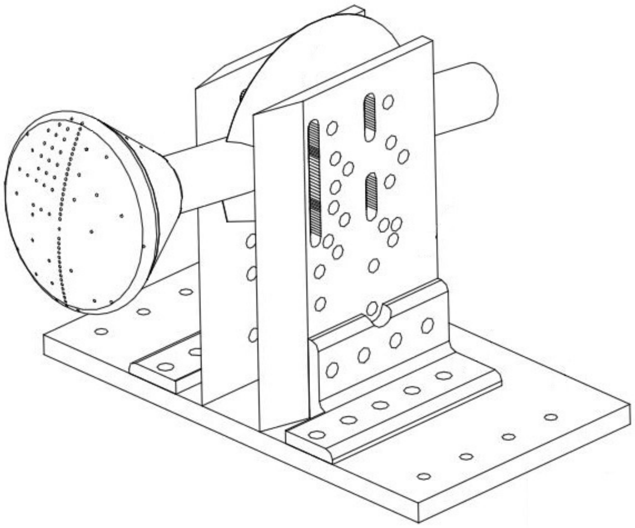

Figure 1: The model and support mechanism.

During a run in T5, models experience large forces; for example, the model used in these studies experienced a drag force that was on the order of 10 kN during the steady flow period, and was considerably higher during the starting flow. The support mechanism must be able to meet this high load requirement. An additional design requirement is the need to be able to change the angle of attack of the model without moving its body off the nozzle centerline. To meet these two requirements, the following system is used (see Figure 1): a pair of vertical plates are mounted on a heavy horizontal plate, which is in turn bolted to the test section rails. Each vertical plate has a set of four holes drilled in it, which correspond to each angle of attack. When a desired angle of attack is selected, four bolts slide through the appropriate set of holes in the vertical plates into four corresponding holes on a circular disk. The disk in turn supports the hollow sting which is firmly fastened to the base of the model.

When the sensors are installed in the model, the wires coming from them are run through the hollow sting to a vacuum-tight feed-through plate in one of the test section flanges. The wires are encased in a thick-walled plastic hose in order to protect them from the hot gas flow.

3.0 THE MOVIES

3.1 Movie Making Procedure

During a run, the measurements from each thermocouple were recorded at 200kHz. These measurements are converted into heat-fluxes via post processing methods, as in [17]. Movies were made by processing the data from the thermocouples using a MATLAB script. Each movie begins and ends 300 microseconds before and after the steady test time. Each frame in a movie represents a time-step in the thermocouple data.

For each frame, the program plots contours of the heat-flux data onto a grid representing the surface of the model. Isolines are placed onto the contours, with MATLAB interpolating the heat-flux between adjacent thermocouples. The MATLAB script repeats this process for each frame, until the movie is finished. For visualization purposes, the outer edge of the model is denoted by a thick black line, and circular markers are placed at the locations of the thermocouples. Several key parameters are listed alongside the heat-flux contours: reservoir pressure, reservoir enthalpy, angle of attack, test start and stop times, free-stream unit Reynolds number, and, if relevant, the trip height. These values are taken from the tables of run conditions from [2], [3], [5], [6]. The scale of the color bar at the bottom of each heat-flux contour is set by the maximum heat-flux recorded by any thermocouple during the test time.

3.2 Movie Analysis Considerations

An area that does not have a thermocouple directly on it will have its value estimated by linear interpolation; this is done by monotonically interpolating the values between neighboring thermocouples. This means that areas more densely populated with thermocouples will better represent the actual distribution of heat-flux than more sparsely populated areas. Furthermore, an isolated thermocouple that records a large heat-flux may lead to a large region of the heat-flux contour reading spuriously high; these issues with interpolation can inhibit the identification of phenomena.

An additional side effect of interpolation is a streaking effect. This happens when two thermocouples have higher/lower heat-flux values than their neighbors. As MATLAB creates a contour, it always makes the path from one given value (a thermocouple) to another monotonic. Hence, if there are two thermocouples registering a large heat-flux relative to the nearest other thermocouples, and there is no thermocouple directly between them, then the path connecting the two thermocouples will read spuriously high. This leads to streaks on the contour plot, as two hot/cold thermocouples are connected by a corresponding hot/cold line. An example of this artifact is presented in the Figure 6.

Bad thermocouples are labeled and their recorded values disregarded. There are two criteria a thermocouple may meet in order to be thrown out. A thermocouple with rapid, non-physical oscillation between low and high heat-flux measurements is disregarded. A thermocouple that constantly records higher or lower non-physical values of heat-flux, in comparison with neighboring thermocouples, is also disregarded. In the latter case, one needs to compare multiple movies to ensure that the thermocouple is indeed faulty. An example is shown in figure 8.

4.0 RESULTS AND CONCLUSION

Periods in time, at a thermocouple, where there are large deviations from the time-averaged value of heat-flux are associated with turbulent spots. These turbulent periods are identified by inspecting the heat-flux movies and looking for large readings. The duration of the hot spots are also considered, as high readings that do not disappear quickly are more likely to be indicative of transition and not noisy measurements. In addition, we also pay attention to their neighbors' values. If multiple thermocouples in a region register large heat-flux, then it is likely that the flow has transitioned in that area. While isolated spots may occur, those recorded on just one thermocouple also indicate possible instrument error, or particle impact. Impacts may be detected by the fact that they are isolated (at most a couple thermocouples will detect the impact) and that they only last for short periods of time. A possible impact is presented in Figure 4.

4.1 Part II

From the runs conducted in Part II ([2]), only two (shots 2368 and 2373) demonstrate the necessary levels of elevated heat-flux to be considered turbulent (see figures 9 and 10). For the two runs that show turbulence, it is difficult to establish what led to transition, as other runs with similar flow parameters do not exhibit transition.

4.2 Part III

In Part III ([3]) most of the shots do not exhibit transition. The shots that do often have large heat fluxes on the right side of the model (see Figure 7). However, this region has only a few thermocouples spread across a large area. From comparison to the other movies, the cause of the apparent “transition” is most likely systematic experimental error rather than boundary layer transition.

4.3 Part V

All movies from Part V ([5]) show laminar heating rates. The few instances in which high heat fluxes were observed are probably the result of either a faulty thermocouple or an impact on the model by a particle.

4.4 Part VI

The majority of examples of turbulent flow occur during Part VI ([6]). Approximately two-thirds of the movies show some degree of transition. A common and notable phenomenon can be seen by examining the two thermocouples directly behind the trips. The first thermocouple directly behind the trips records a much lower heat-flux than the second thermocouple directly behind the trips. Furthermore, the second thermocouple records greater heat-flux than would normally be expected. This pattern of low heat-flux followed immediately by large heat-flux (following a streamline in the boundary layer of the blunt body) is attributed to the influence of the trips on the flow field ([8]). The trips introduce instability in the flow, which leads to transition. Notably, the height of the trips (for the values of trip height used in this study) does not seem to have any effect on the location of the turbulent spot. This could be explained by the boundary layer thickness being small relative to the height of the trips or a lack of spatial resolution due to thermocouple placement. A snapshot of one such experiment is presented in Figure 5. Every run conducted with a trip height of 0 and with a large unit Reynolds number (approximately 5,000,000 1/m) exhibited turbulent flow on the leeward side of the model. These were the only conditions to yield this result.

It is also important to note that the region where the trip is located almost certainly has incorrect values for heat-flux plotted. The trip prevents thermocouples from being placed in the area, and hence MATLAB interpolates the heat-flux values in the region.

4.5 Conclusion

This report has discussed the observations and conclusions that can be drawn from heat-flux movies of hyper-velocity flow over a CEV candidate shape. For three parts of the study ([2], [3], [5]), few movies demonstrated transition. However, when trips simulating isolated roughness effects were used ([6]), transition occurred in a majority of the runs.

ACKNOWLEDGEMENTS

We would like to thank Eric Marineau and Stuart Lawrence for their work on [1–6] and [16] that allowed us to present this new data analysis.

The initial heat-flux experiments were sponsored by the NASA Ames Research Center, for which Dr. Joseph Olejniczak was the principal investigator, and Dr. Deepak Bose was the program manager. The present analysis was sponsored by AFOSR/National Center for Hypersonic Research in Laminar-Turbulent Transition, for which Dr. John Schmisseur is the program manager. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

5.0 IMAGES FROM THE MOVIES

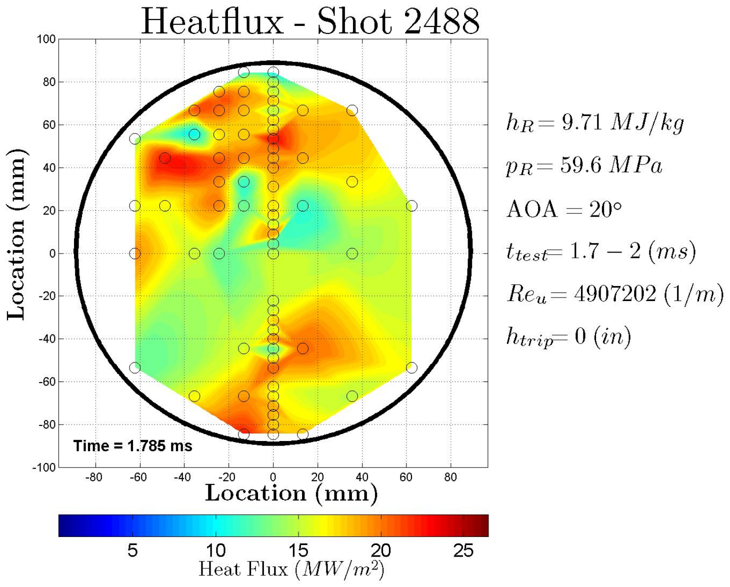

Figure 2: An example of turbulent flow. Note the high heat-flux zones in the leeward region, located on the upper part of the model.

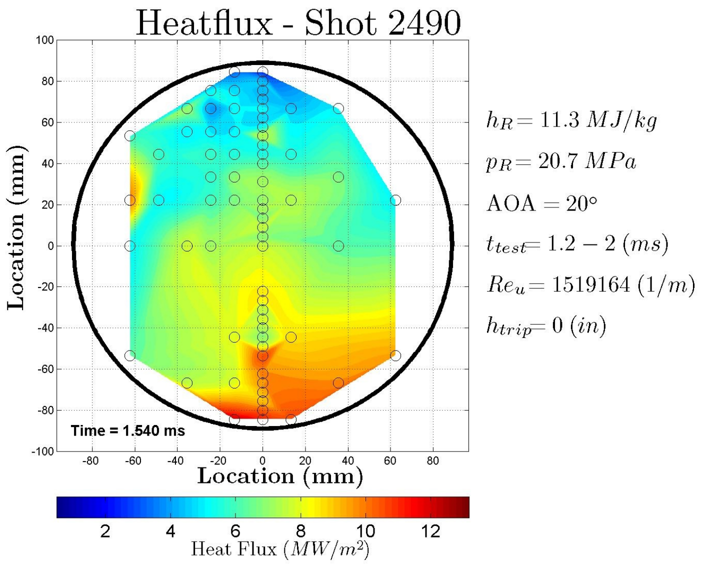

Figure 3: An example of laminar flow. The leeward side has lower heat-flux than the windward side, and there are no areas of higher than normal heat-flux.

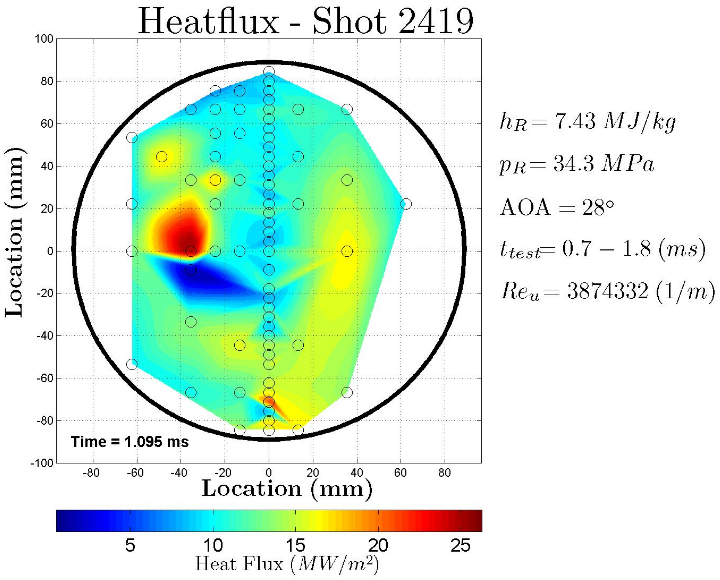

Figure 4: An example of a possible impact. Note that only one, isolated thermocouple has a large reading.

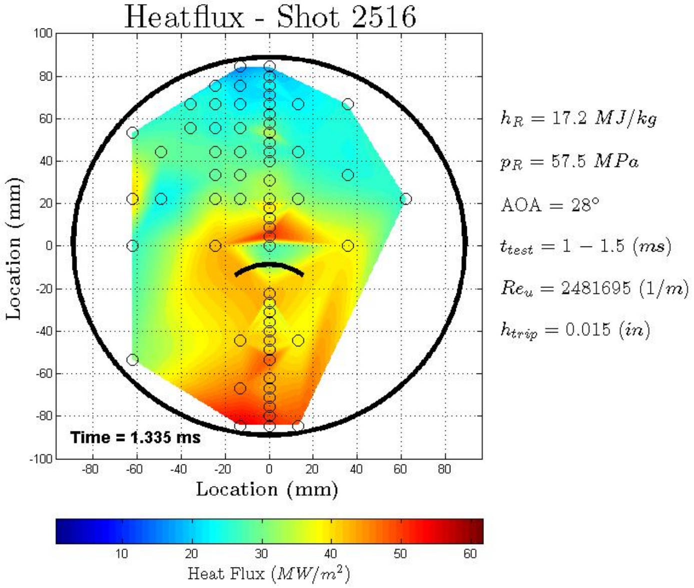

Figure 5: An example of the trip creating a turbulent region, which then re-laminarizes as it continues on the body. The black arc under the center of the model represents the location of the trips.

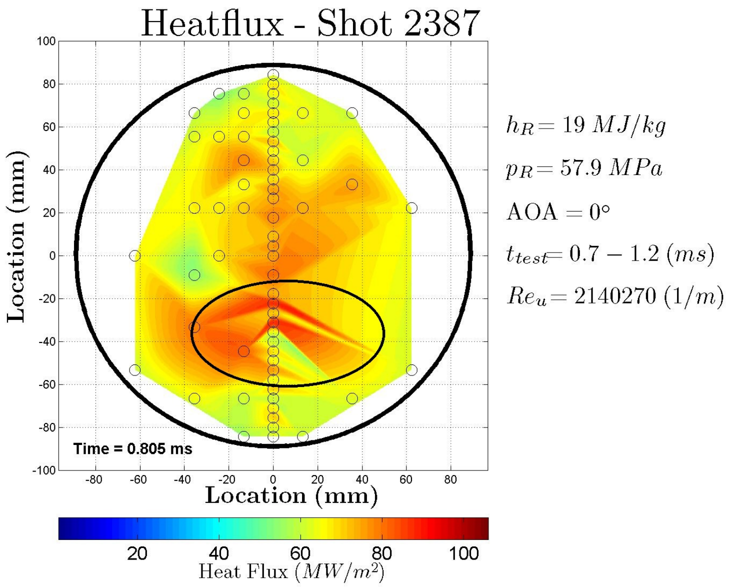

Figure 6: This is an example of the streaking artifact that can occur due to MATLAB's interpolation. The artifact is most obvious in the region circled below.

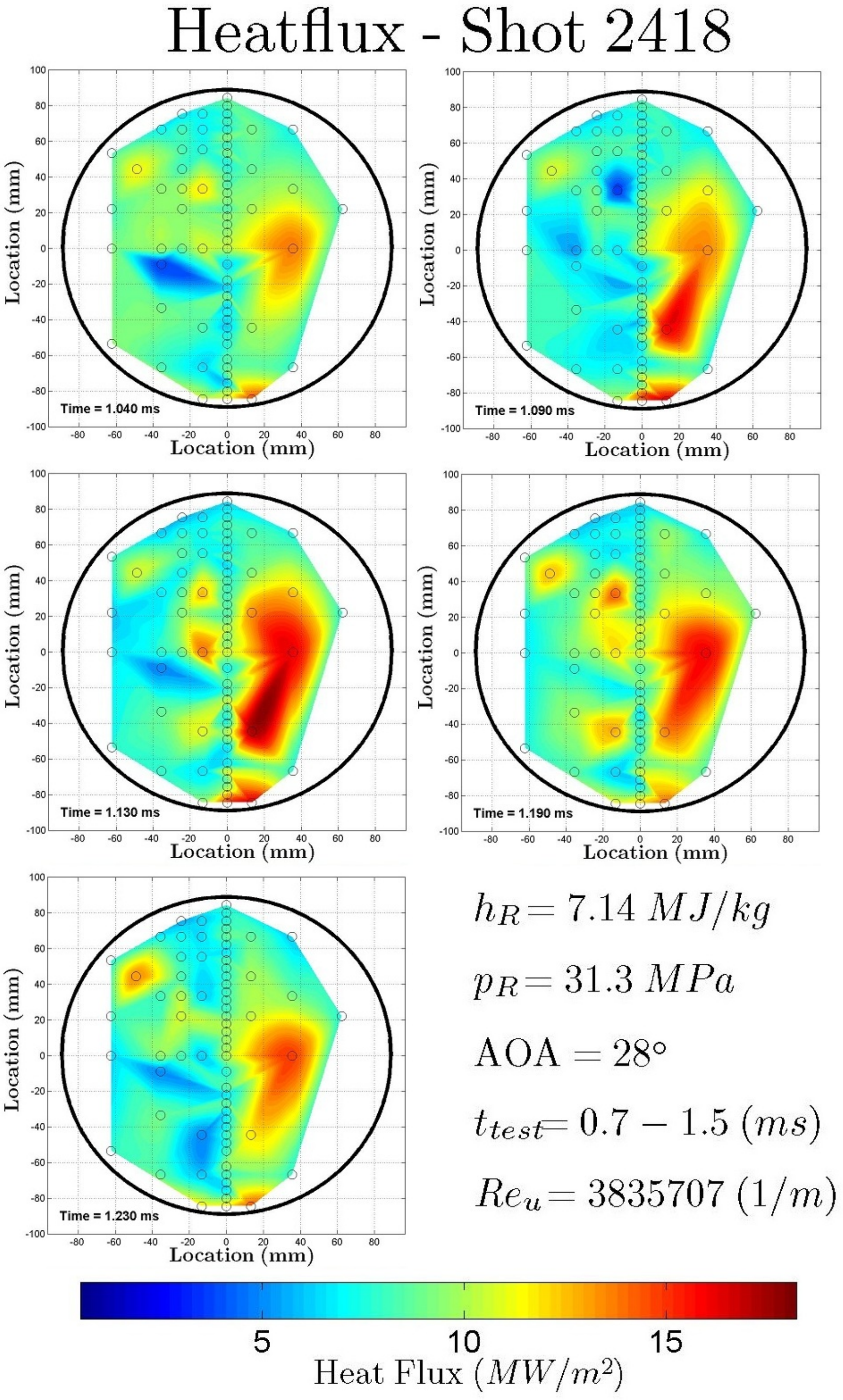

Figure 7: The evolution of heat-flux during run 2418 of Part III. Note the large, turbulent heating region on the right side of the body.

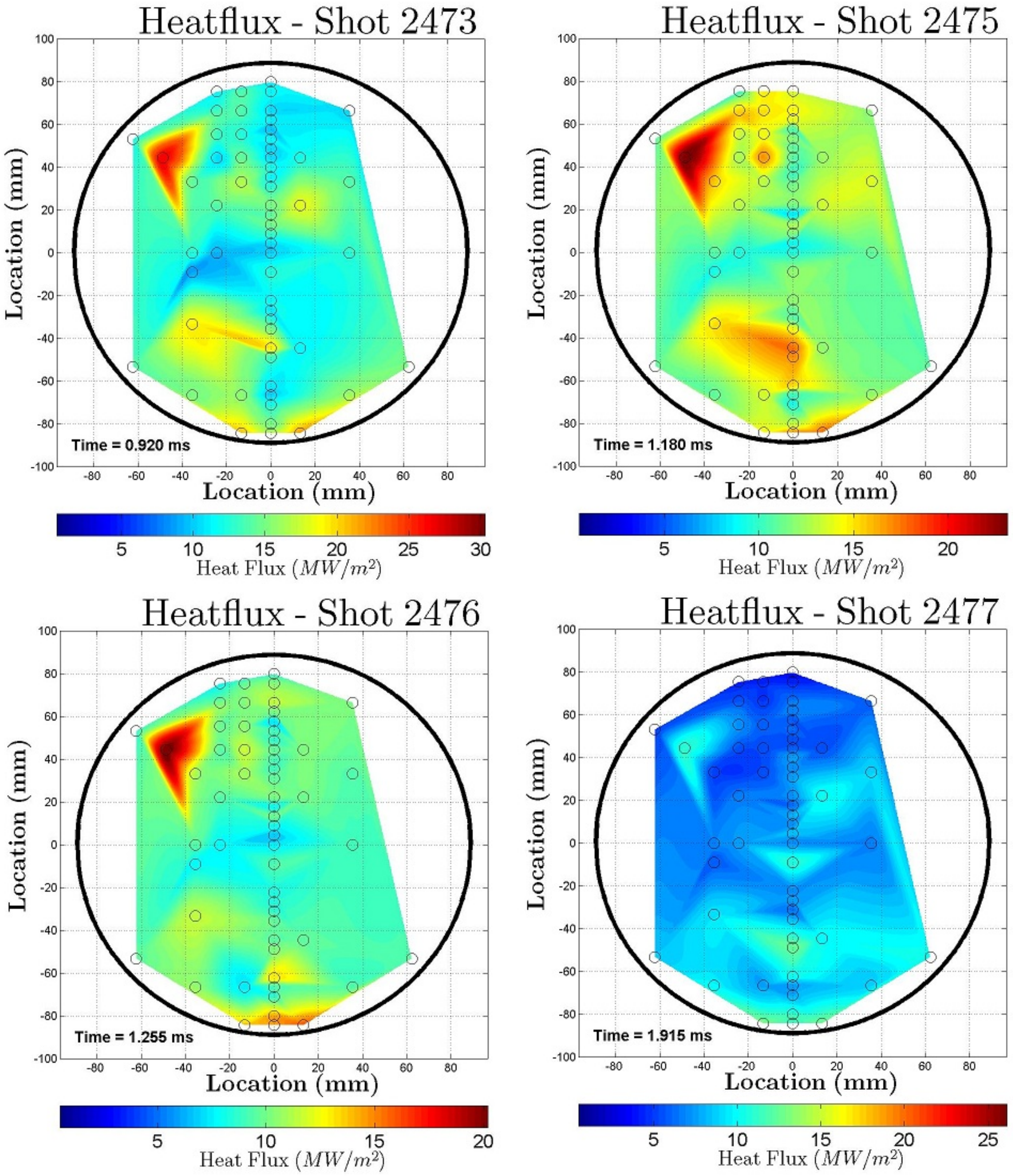

Figure 8: The following four images are each taken from different shots. They provide a good example of a bad thermocouple. We can see that for different shots, the same thermocouple in the upper left hand corner continues to register a higher heat-flux larger value than its neighbors.

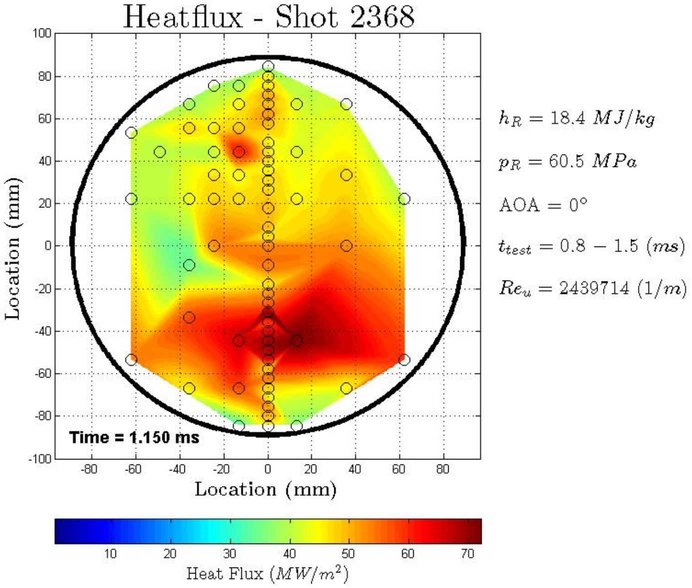

Figure 9: A frame from the turbulent period of run 2368.

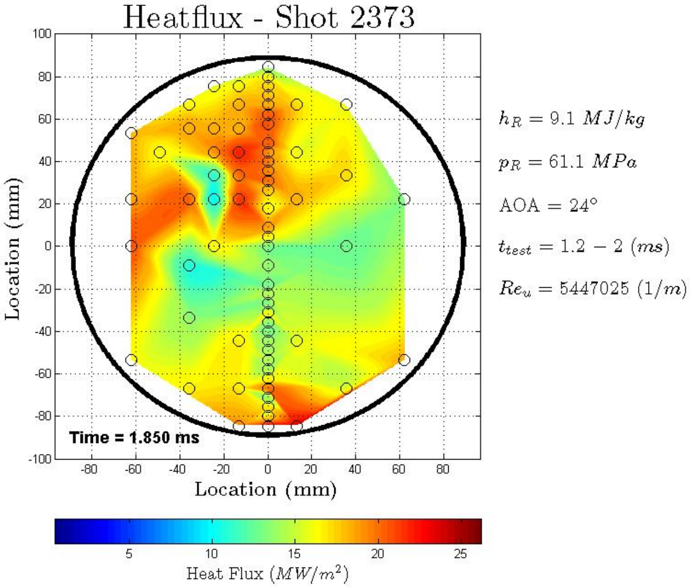

Figure 10: A frame from the turbulent period of run 2373.

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