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FLOW VISUALIZATION STUDY IN HIGH ASPECT RATIO COOLING CHANNELS FOR ROCKET ENGINES

Michael L. Meyer
NASA Lewis Research Center
Cleveland, Ohio 44135

James E. Giuliani
Ohio Aerospace Institute
Brook Park, Ohio 44142

INTRODUCTION:

The structural integrity of high pressure liquid propellant rocket engine thrust chambers is typically maintained through regenerative cooling. The coolant flows through passages formed either by constructing the chamber liner from tubes or by milling channels in a solid liner. Recently, Carlile and Quentmeyer[1] showed life extending advantages (by lowering hot gas wall temperatures) of milling channels with larger height to width aspect ratios (AR > 4) than the traditional, approximately square cross section, passages. Further, the total coolant pressure drop in the thrust chamber could also be reduced, resulting in lower turbomachinery power requirements. High aspect ratio cooling channels could offer many benefits to designers developing new high performance engines, such as the European Vulcain engine (which uses an aspect ratio up to 9)[2]. With platelet manufacturing technology, channel aspect ratios up to 15 could be formed offering potentially greater benefits[3].

Some issues still exist with the high aspect ratio coolant channels. In a coolant passage of circular or square cross section, strong secondary vortices develop as the fluid passes through the curved throat region. These vortices mix the fluid and bring lower temperature coolant to the hot wall. Typically, the circulation enhances the heat transfer at the hot gas wall by about 40% over a straight channel[4]. The effect that increasing channel aspect ratio has on the curvature heat transfer enhancement has not been sufficiently studied. If the increase in aspect ratio degrades the secondary flow, the fluid mixing will be reduced. Analysis has shown that reduced coolant mixing will result in significantly higher wall temperatures, due to thermal stratification in the coolant, thus decreasing the benefits of the high aspect ratio geometry[5]. A better understanding of the fundamental flow phenomena in high aspect ratio channels with curvature is needed to fully evaluate the benefits of this geometry.

The fluid dynamic and conjugate heat transfer problem of high aspect ratio rocket engine coolant channels are being investigated numerically, but these efforts have been hampered by a lack of validating data[2,6]. Wall temperature data is available for the conjugate problem for channels without curvature and aspect ratio = 5.0[1], and unheated fluid dynamic data are available for square and circular cross section channels with curvature at Reynold's numbers up to 40,000[7,8]. But the effects of aspect ratio on secondary flow development have not been experimentally studied.

To provide some insight into the effects of channel aspect ratio on secondary flow and to qualitatively provide anchoring for the numerical codes, a flow visualization experiment was initiated at the NASA Lewis

Research Center.

APPARATUS:

The experimental test rig, shown in figure. 1, was designed to permit visualization of the secondary flow structure that develops in a turning rectangular channel. The test rig consists of upper and lower plexiglass plates, which form the channel top and bottom, and two strips of plexiglass which make up the side walls. The plexiglass strips fit into grooves cut into the upper and lower plates. The grooves are spaced 1.25 in. apart and provide a constant channel width. Wall strips of varying heights may be placed into the groves to change the height of the channel. Aspect ratios from 1.0 to 5.0 are possible and a wall height was selected for this experiment that gave the channel an aspect ratio of 5.0 (1.25 in. width x 0.25 in. height; NOTE: In this experiment, the channel is laying on its side so height and width are interchanged with respect to an actual cooling channel dimensions). The total length of the channel is 11.3 ft. and consists of two 5.0 ft. straight sections and a 180° bend in the center. Upon entering the channel, the flow first passes through a 5.0 ft. straight section where disturbances dissipate and the flow is allowed to develop. The channel then turns 180° with a 5.0 in. centerline radius of curvature. The channel continues straight for an additional 5.0 ft. to the flow outlet. Water is pumped through the system either by normal water supply pressure or by an additional pump. Reynolds numbers based on hydraulic diameter up to 40,000 can be obtained with the normal supply pressure and Reynolds numbers up to 100,000 are possible with the pump.

To visualize the flow structure in the turning section, the hydrogen bubble technique is used to provide a seedant for the flow[9,10]. With this technique, hydrogen bubbles are formed on thin wires placed within the flow field. The wires form the cathode (negative) pole of a DC circuit and an additional wire, which is placed non-intrusively in the flow, forms the anode (positive) pole. When a current is applied to the circuit, electrolysis takes place forming oxygen on the anode and hydrogen on the cathode. As hydrogen bubbles form on the cathode wires, the flow strips them away. Five cathode wires are placed vertically across the width of the channel and 1.0" upstream of the turning section. The size of the bubbles generated is a function of the wire diameter, conductivity of the water, applied voltage and flowrate[9]. The power supply used to generate the hydrogen bubbles is a 160 V DC with a 100 mA current limit, and wire diameters of 0.002", 0.005" and 0.010" were interchanged.

A high intensity photographic spot light was used to illuminate the hydrogen bubbles from above as they flowed through the turning section. The beam from the light source was collimated with a series of slits so that only a thin plane of the flow was illuminated. A standard VHS camera and recorder were used to record the illuminated particle streaks. The camera was placed perpendicular to the plane of interest and to minimize the distortion caused by the camera focusing through the curved plexiglass wall, a triangular window was seated against the channel wall and filled with water. The side of the window provides a flat surface parallel to the focus plane and the water filled cavity provides a more uniform index of refraction. The optical compensating window was sealed to the test rig with RTV and could be removed, cleaned and re-attached at a different location. Video image data was recorded at 1 inch upstream of the bend, 3 inch downstream of the bend and at 0°, 30°, 60°, 90°, 120°, 150° and 180° from the start of the bend.

DATA ANALYSIS:

Analysis of the raw video images provided some insight into the flow structure, however, results were somewhat inconclusive. A problem with this type of flow visualization is that the particle streaks remain illuminated for only 2 to 3 video frames before passing out of the light sheet. Once a particle enters a particular region, only a brief view of the flow structure is given. To better understand where vortices and velocity gradients occur in the channel, a computer algorithm was developed to enhance the digitized raw video images, resolve vectors from particle streaks, and infer particle direction by analyzing several sequential frames.

Individual video frames were digitized to a 620 pixel wide by 160 pixel high image with a 15 pixel border surrounding the actual channel. Figure 2 shows a digitized image from a video frame taken at a Reynolds number of 6,800. The algorithm first scanned the digitized image looking for local gradients in pixel brightness to find particle streaks. Once a gradient was encountered, marking a particle streak, the algorithm searched along the gradient to find the two endpoints. Figure 3 shows the individual particle streaks that were calculated from the image in figure 2. Resolving the particle streaks by processing the brightness gradients worked well as many streaks were resolved that are too subtle for the unaided eye. Considering local gradients also eliminated the problem of resolving streaks in regions where glare on the plexiglass side wall was encountered. While glare on the side wall caused the background to be of differing intensity levels throughout the image, its change from pixel to pixel was small and was therefore invisible to local gradient calculations.

Once the particle streaks in individual frames are resolved, the algorithm compares sequential frames to see if a particle streak in frame 1 at time 0 continues in frame 2 at time Δt. For each vector in frame 1, frame 2 is searched to see if any endpoints match those in frame 1. If vectors in frame 1 and frame 2 have a matching endpoint, then a multiple frame particle streak has been found and the direction of the particle is inferred by the sequence of the frames. A circle is placed on the head of the vector to denote direction.

Figure 4 shows the results of processing 30 sequential frames from video taken at 30° from the start of the bend at a Reynolds number of 6,800 based on hydraulic diameter. Only resolved vectors with magnitudes greater than 20 pixels are considered. In this figure, the primary flow direction is out of the page, with the outer wall of the bend on the left and the inner wall on the right. Here the classical secondary flow can be seen, with the velocity on the upper and lower surfaces travelling towards the inner wall and the centerline velocity travelling towards the outer wall. This is the result of a pair of horizontally elongated vortices stacked on top of each other. It should be noted that the flow is not perfectly steady and some particle streaks represent momentary fluctuation in the flow structure. Some particles can also be seen being stripped from the centerline flow by the flow at the wall. As Reynolds number is increased, resolving the particle streaks becomes increasingly difficult. Improved experimental techniques will be required to capture the secondary flow structures at higher velocities.

REFERENCES

1. Carlile, J. A., Quentmeyer, R. J., "An Experimental Investigation of High-Aspect-Ratio Cooling Passages," NASA TM 105679, AIAA Paper 92-3154, 1992.

2. LeBail, F., Popp, M., "Numerical Analysis of High Apect Ratio Cooling Passage Flow and Heat Transfer," AIAA Paper 93-1829, 1993.

3. Tobin, S., Mueggenburg, H., Burkhardt, W., "Formed Platelet Liner Concept for Regeneratively Cooled Chambers," AIAA Paper 90-2117, July 1990.

4. Hendricks, R. C., Simon, F. F., "Heat Transfer to Hydrogen in a Curved Tube," presented at the ASME Meeting, Philadelphia, November, 1963.

5. Kacynski, K. J.,"Thermal Stratification Potential in Rocket Engine Coolant Channels," NASA TM 4378, 1992.

6. Yagley, J. A., Feng, J., Merkle, C. L.,"CFD Analyses of Coolant Channel Flowfields," AIAA Paper 93-1830, June 1993.

7. Taylor, A. M. K. P., Whitelaw, J. H., Yiannekis, M., "Measurements of Laminar and Turbulent Flow in a Curved Duct with Thin Inlet Boundary Layers," NASA Contractor Report 3367, 1981.

8. Humphrey, J. A. C., Launder, B. E., "Developing Turbulent Flow in Strongly Curved Passages of Square and Circular Cross Section," Final Technical Report for the Office of Naval Research, AD-A143 279, 1984.

9. Davis, W., Fox, R. W., "An Evaluation of the Hydrogen Bubble Technique for the Quantitative Determination of Fluid Velocities Within Clear Tubes," Journal of Basic Engineering, Trans. ASME, December 1967, pp. 771-781.

10. Tory, A. C., Haywood, K. H., "The Hydrogen Bubble Technique of Flow Visualization: Factors Affecting Bubble Size and Buoyancy," Fluids Engineering Conference, ASME Paper 71-FE-36, May 1971, Pittsburgh, Pa.

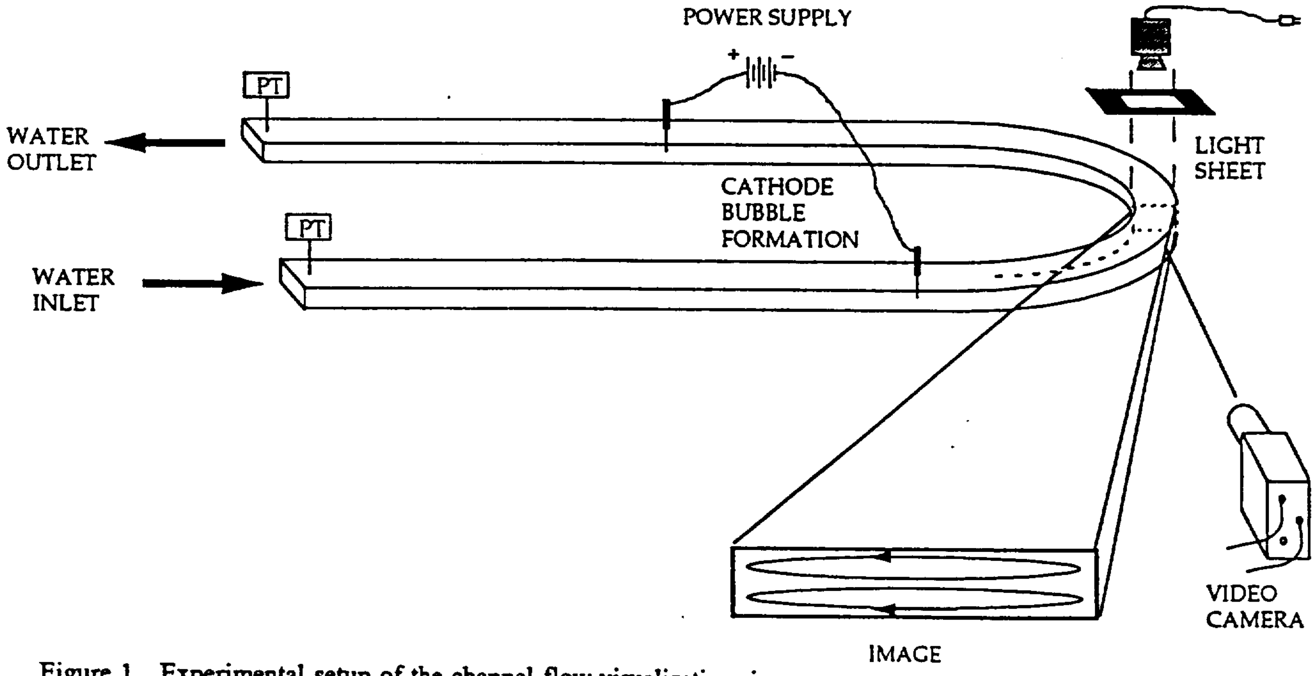

Figure 1. Experimental setup of the channel flow visualization rig.

Figure 2 - Digitized video image

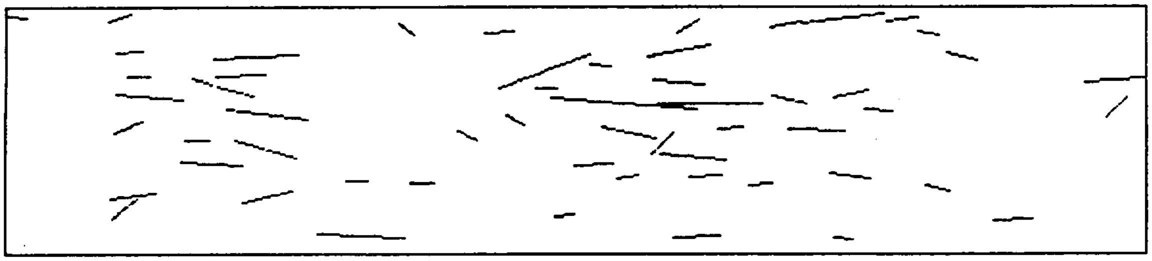

Figure 3 - Single frame particle streaks

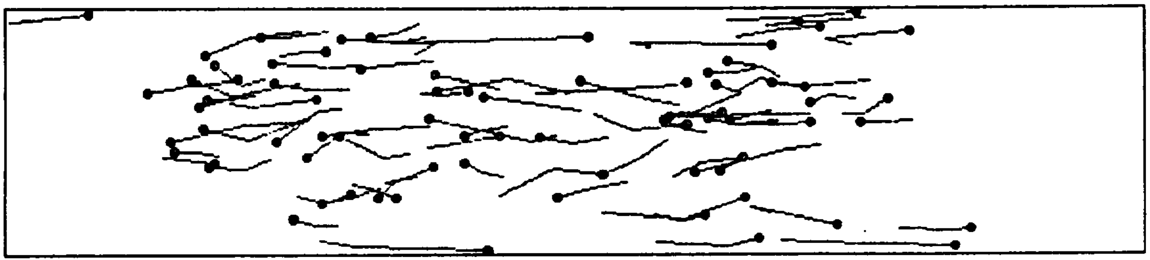

Figure 4 - Multiple frame particle streaks at Re=6,800 @ 30°