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FLUID FLOW AND HEAT CONVECTION STUDIES FOR ACTIVELY COOLED AIRFRAMES

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Introduction

This report details progress made on the jet impingement - liquid crystal - digital imaging experiment. With the design phase complete, the experiment is currently in the construction phase. In order to reach this phase two design related issues were resolved.

The first issue was to determine NASP leading edge active cooling design parameters. Meetings were arranged with personnel at SAIC International, Torrance, CA in order to obtain recent publications [1,2] that characterized expected leading edge heat fluxes as well as other details of NASP operating conditions. The information in these publications was used to estimate minimum and maximum jet Reynolds numbers needed to accomplish the required leading edge cooling, and to determine the parameters of the experiment. The details of this analysis are shown in Appendix A. One of the concerns for the NASP design is that of thermal stress due to large surface temperature gradients. Using a series of circular jets to cool the leading edge will cause a non uniform temperature distribution and potentially large thermal stresses. Therefore it was decided to explore the feasibility of using a slot jet to cool the leading edge. The literature contains many investigations into circular jet heat transfer [3,4] but few investigations of slot jet heat transfer [5]. The first experiments will be done on circular jets impinging on a flat plate and results compared to previously published data to establish the accuracy of the method. Subsequent experiments will be slot jets impinging on full scale models of the NASP leading edge. Table 1 shows the range of parameters to be explored.

Table 1. Experimental parameter variation.

	Minimum	Maximum
Re	9,000	50,000
Flow Rate	0.008 m^3/s	0.024 m^3/s
Jet Hydraulic Diameter	2 mm	8 mm
Nozzle to Surface Spacing	0.5 mm	4. mm
Heat Flux	3×10^5 W/m^2	8×10^6 W/m^2
Surface Temperature	810 K	1922 K

Next a preliminary design of the experiment was done. Previous papers which used a similar experimental technique [6,7] were studied and elements of those experiments adapted to the jet impingement study. Trade-off studies were conducted to determine which design was the least expensive, easy to construct, and easy to use. Once the final design was settled, vendors were contacted to verify that equipment could be obtained to meet our specifications. Much of the equipment required to complete the construction of the experiment has been ordered or received. The material status list is shown in Appendix B.

Computer Hardware

The jet impingement experiment requires various computer controlled data acquisition equipment and instruments. The central part of the system is a 486 - 33 MHz PC with a Data Translations DT - 3851 frame grabber card and a DT - 2812 data acquisition card. Since these two type of cards are typically not used in the same computer system they were both purchased from the same manufacturer in order to minimize conflicts with hardware and software. The instrumentation includes a Sony XC - 75 CCD camera with a Tamron 35 - 135 mm macro lens that will supply the frame grabber card analog images of the thermochromic liquid crystals (TLCs) that are spray painted on the model. The analog images are displayed on a Sony PVM 1344 Q monitor, while the digital images or other information about the experiment are displayed on the computers SVGA monitor. The data acquisition card will be used to collect digital data from an EG&G model FT - 16 turbine flow meter, an Omega Px - 303 pressure transducer and 4 RTD temperature transducers. The video, temperature, pressure, and flow data will be processed by the computer, either in real time or after the experiment, to obtain Nusselt numbers.

Computer Software

Several pieces of software are being written in order to use this experimental technique. The digital image recording is the most complicated software. Fortunately Data Translations provides many of the necessary subroutines for the frame grabbing. Since Data Translations provides their subroutines in C a Borland C++ compiler has been purchased and a main program has been written which calls several of the provided subroutines to accomplish grabbing a video image from the CCD camera and transferring it from the DRAM of the frame grabber card to the computer DRAM. At the termination of the program, the frames in DRAM are written to the hard drive for long term storage. For permanent storage these frames can also be sent to tape. Later the program will be modified to allow the frames to be retrieved from disk or tape for further processing.

Once the instrumentation and data acquisition card are installed a program will be written using vendor supplied subroutines which will control the instrumentation and store or pass the data to the data reduction program.

When the all the data has been acquired, a program will process all the data and determine the final output. This program will incorporate image filtering and boundary following routines to locate the position of the constant temperature contours as represented by the liquid crystals. The output from this program will be the needed Nusselt number data. The format of the output data will be such that it can be easily displayed using a standard graphics package such as Stanford Graphics.

Piping

A diagram of the experimental rig is shown in Fig 1. Most of the piping is 1 inch Schedule 40 PVC which is easy to work with and has a maximum pressure rating of 280 psig, well above the 80 psig maximum possible pressure for this experiment. Air is available throughout Engineering IV at 80 psig. The building air first enters a centrifugal separator which removes water that tends to condense in the lines. The air pressure is then reduced from 80 psig to about 8 psig using a Moore model 42H - 100 precision pressure regulator. The air is then separated again to remove any water which may have condensed when the pressure was dropped. From there the air flows past temperature, pressure, and flow transducers to the jet nozzle and finally impinges on the test section coated with liquid crystal paint.

If it becomes necessary to use other gases to vary the parameters of the experiment this system can be easily adapted. In place of the building air, a large 100 psig tank can be installed. This tank could hold a gas other than air (helium is a likely candidate since helium properties are close to those of hydrogen, which will no doubt be the actual NASP coolant).

Mechanical

At time zero, the test surface must be at a uniform temperature above the transition temperature of the liquid crystals. At the same time the jet must be at steady state. This requires that the jet be physically moved into contact with the test surface at time zero. To do this the heating device (an oven or warm air blower) is moved away from the test surface while at the same time the jet is moved toward the surface. As soon as the nozzle is locked into position a shield separating the nozzle and test section is removed. The nozzle will be made mobile by connecting it to the rest of the piping by a flexible tube, mounting it on a rail, and moving it with a mechanical actuator.

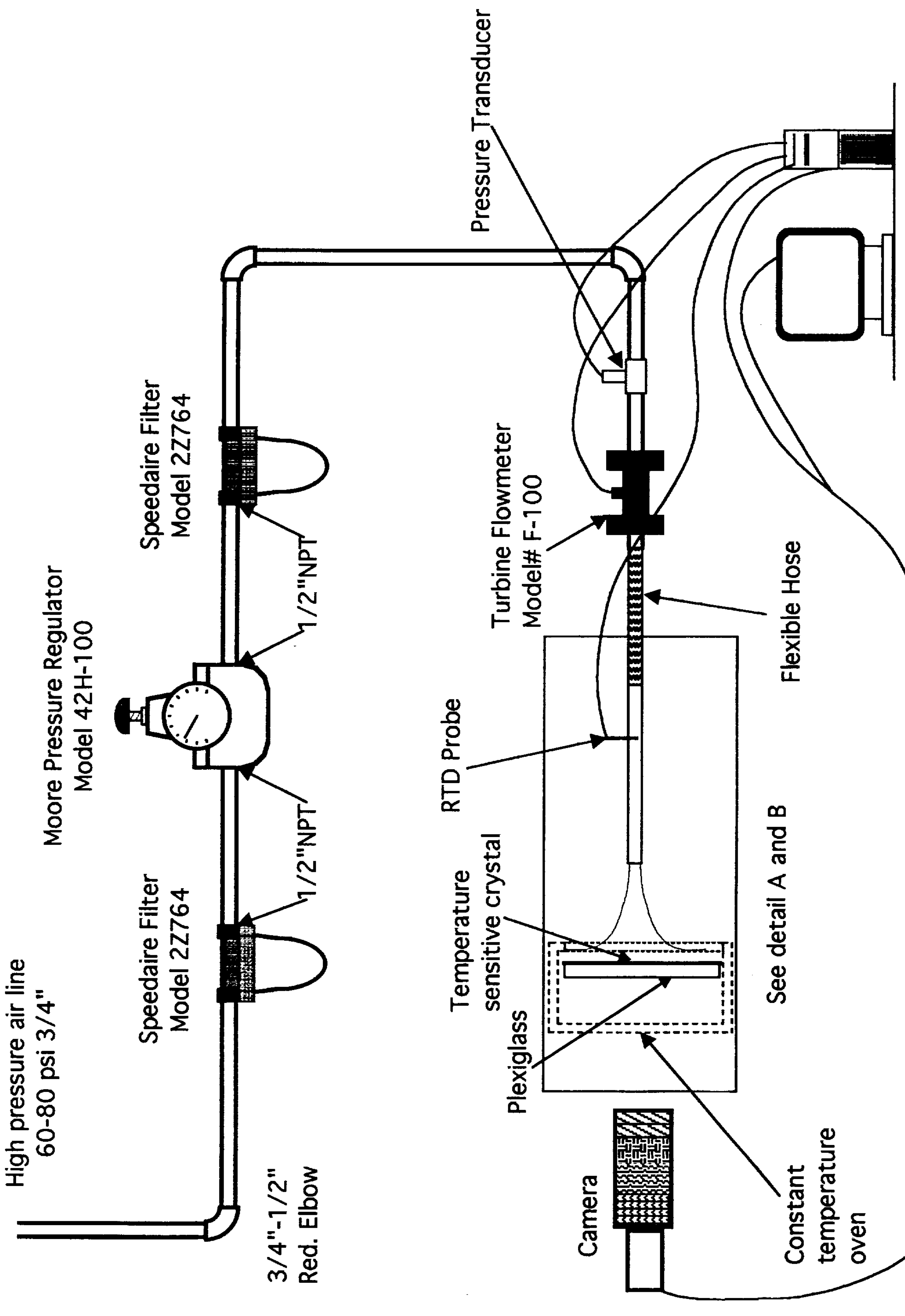
Liquid Crystals

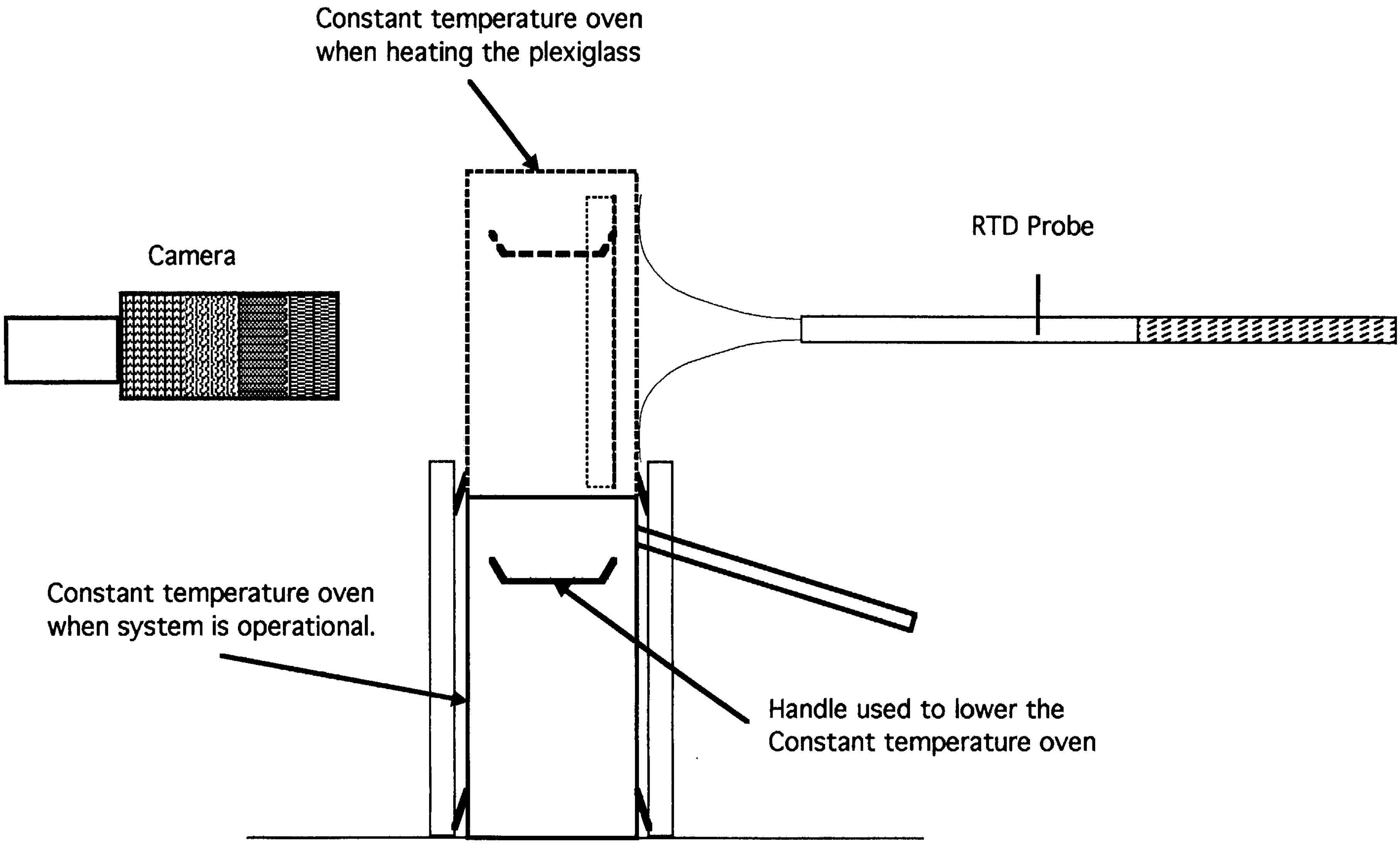
The TLCs are supplied by Halcrest Inc. in a form suitable for use in an air brush paint gun. The crystals can, to some extent, be " tuned " to undergo color change at a specified temperature. The bandwidth of the color change can also be specified between 1 °C and 30 °C. A smaller bandwidth will give a sharper the constant temperature contour and yield a higher accuracy. Samples have been shipped and testing will be done to determine which TLCs produce the sharpest digital image.

References

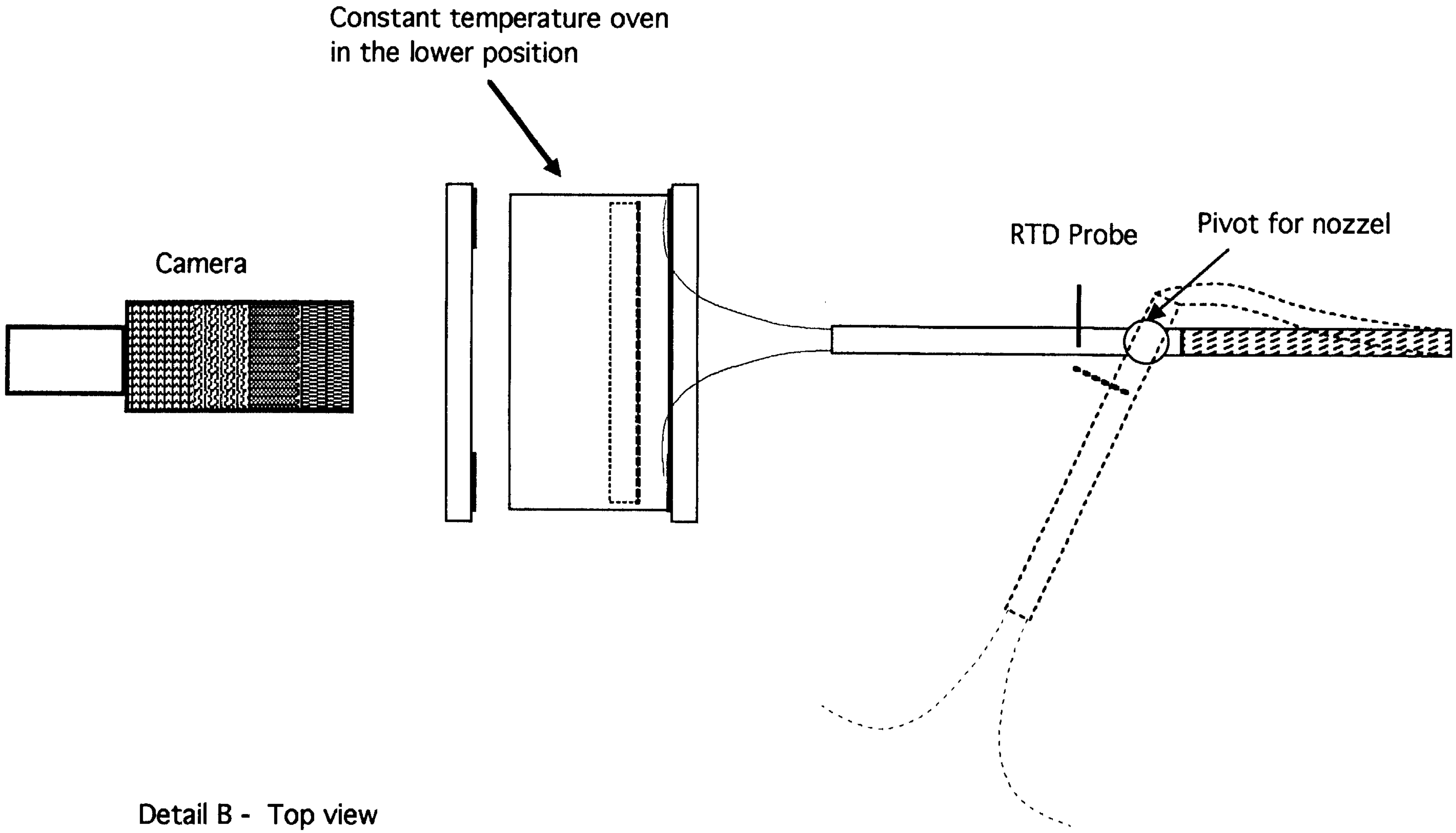
1. Baker, N. R., "Jet Impingement Cooling: Review and Applicability," Second NASP Technology Symposium, November 5 - 7, (1986).
2. Friestad, R., and Berkel, T., "Leading Edge Structural Design Criteria," McDonnell Douglas Report No. 1064900, March 20, (1992).
3. Shoukri, M., and Calka, A., "On the Heat Transfer Characteristics of Constrained Air Jets Impinging on a Flat Surface," *Int. J. Heat Mass Transfer*, Vol. 30, No. 1, pp. 205-208, (1987).
4. Goldstein, R. J., and Seol, W. S., "Heat Transfer to a Row of Impinging Circular Air Jets Including the Effect of Entrainment," *Int. J. Heat Mass Transfer*, Vol. 34, No. 8, pp. 2133-2147, (1991).
5. Gardon R., and Akfirat, J., C., "Heat Transfer Characteristics of Impinging Two - Dimensional Air Jets," Trans. ASME, paper No. 65--HT-20, pp. 101-107, (1966).
6. Baughn, J. W., and Yan, X., "Local Heat Transfer Measurements in Square Ducts with Transverse Ribs," ASME HTD-Vol. 202, Enhanced Heat Transfer, (1992).
7. Wolfersdorf J. V., Hoecker, R., and Sattelmayer, T., "A Hybrid Transient Step-Heating Heat Transfer Measurement Technique Using Heater Foils and Liquid-Crystal Thermography," ASME J. Heat Transfer, Vol. 115, (1993).

Figure 1: Schematic of Experimental Rig





Detail A - Side view



Detail B - Top view

Appendix A

Leading Edge Cooling Analysis and Design

In order to design the jet impingement cooling system for the NASP leading edge, heat flux predictions were obtained from [A1]. Combining the heat flux predictions with estimates of the jet impingement heat transfer coefficients from other sources [A2,A3] a preliminary cooling system can be designed. It will be this configuration that is explored in the jet impingement experiment.

Using laminar Fay & Riddell theory a parametric study of leading edge heat fluxes is presented [A1]. In the analysis, wall temperature and leading edge radius of curvature are varied. Heat flux curves are presented for both the upper and lower surface, at all times during ascent and descent. It was decided to investigate the worst case heat flux which occurs on the lower surface during ascent with a leading edge radius of 0.508 cm, Mach number of 18 and a wall temperature of 810K. The method of determining the design of the jet impingement cooling system is illustrated below. Figure A1 shows the energy balance.

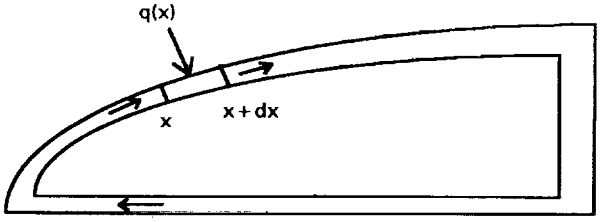


Figure A1. Energy balance for the leading edge.

The energy balance is

$$\dot{m}c_pT\Big|_x - \dot{m}c_pT\Big|_{x+dx} + q(x) = 0 \qquad (1)$$

A Taylor series expansion about x and a rearrangement of terms yields,

$$\dot{m}c_p\frac{dT_b}{dx} = q(x) \qquad (2)$$

An energy balance on the wall shows that,

$$q(x) = h(x)\,[\,T_w(x) - T_b(x)\,] \qquad (3)$$

The bulk fluid temperature is obtained by integrating Eq. (2); hence,

$$T_b(x) \;=\; T_{b_0} + \frac{1}{\dot{m}c_p}\int_0^x q(x)\,dx \tag{4}$$

Equation (4) can also be expressed in terms of the jet Reynolds number based on the hydraulic diameter of the slot.

$$T_b(x) \;=\; T_{b_0} + \frac{2}{L\mu\, c_p \mathrm{Re}_{d_h}}\int_0^x q(x)\,dx \tag{5}$$

Equations (4) and (5) can be used in iterative manor to design the jet nozzle. Generally h(x) is a function of Re, and the slot height divided by the distance from the nozzle exit plane to the impingement surface. Therefore these parameters are chosen first, and then $T_b(x)$ is calculated from Eq. (5). The heat transfer coefficient h(x), is obtained from references [A2,A3]. As x increases, h decreases: however, it is assumed that some sort of enhanced surface can be provided (such as transverse ribs or pin fins) such that h does not drop below 1,000 W/m^2 K. $T_b(x)$ and h(x) are substituted into Eq. (3), which is then solved for $T_w(x)$. q(x) is known for $T_w(x)$ equal to 810 K: therefore if the solution to Eq. (3) is not close to this value, new parameters are chosen and the process repeated until convergence is obtained. A computer program was written to handle the numerical integration in Eq. (5) and to speed up the iterative process. Tables A2 and A3 show sample output from a single iteration.

Table A2. Jet impingement design program output part 1.

RE	14502.6
NU	101.8
JET STAGNATION h	12877.1 W/m^2 K
SLOT HEIGHT	0.12 cm
SLOT LENGTH	10.0 cm
VOLUMETRIC FLOW RATE	0.04075 m^3/s
MASS FLOW RATE	0.00500 kg/s
NOZZLE EXIT VELOCITY	339.6 m/s
NOZZLE EXIT MACH NUMBER	0.316 dimensionless
NOZZLE DIAMETER / DISTANCE TO PLATE	20.0 dimensionless

Table A3. Jet impingement design program output, part 2.

x cm	q W/m^2	h W/m^2 K	T WALL K	T BULK K
0.000	7.090E+06	12877.1	750.6	200.0
0.254	6.390E+06	11756.6	792.4	248.9
0.508	4.260E+06	10733.5	684.4	287.6
0.762	1.770E+06	9799.5	490.1	309.4
1.270	1.560E+06	8168.3	524.6	333.6
2.540	1.340E+06	5181.4	644.8	386.2
5.080	9.200E+05	2084.8	909.5	468.2
7.620	7.100E+05	1000.0	1237.4	527.4
15.240	5.000E+05	1000.0	1159.1	659.1
30.480	3.500E+05	1000.0	1194.1	844.1
50.800	2.100E+05	1000.0	1216.7	1006.7

Table A3 shows that this jet is capable of keeping the wall temperature below 810 K at a distance of about A4 cm from the stagnation point. At the 4 cm point additional cool gas must be injected to reduce the bulk temperature and maintain a wall temperature below 810 K. Note that a sharp drop in wall temperature occurs at about 7 mm from the stagnation point, and is due to a sharp drop in wall heat flux at about the same location. In general, the results show that sufficient cooling can be achieved with a wide range of Reynolds numbers. As the coolant moves away from the leading edge the bulk temperature rises and additional coolant must be injected in order to maintain an acceptable wall temperature. For a Reynolds number of 10,000, the additional coolant must be injected at about 3.0 cm from the stagnation point, however for a Reynolds number 46,000 the injection is not necessary until about 11 cm.

References

A1. Friestad, R., and Berkel, T., "Leading Edge Structural Design Criteria," McDonnell Douglas Report No. 1064900, March 20, (1992).

A2. Gardon R., and Akfirat, J., C., "Heat Transfer Characteristics of Impinging Two - Dimensional Air Jets," Trans. ASME, paper No. 65--HT-20, pp. 101-107, (1966).

A3. Gau, C., and Chung, C. M., "Surface Curvature Effect on Slot-Air-Jet Impingement Cooling Flow and Heat Transfer Process," ASME J. Heat Transfer, Vol. 113, pp 858-864, (1991).

Appendix B

Equipment and Materials

Equipment / Material	Status
486 - 33 MHz PC	Operational
DT 3851 Frame Grabber	Installed, Operational
DT 2812 Data Acquisition Card	Not Ordered
Sony XC - 75 CCD Camera	Installed, Operational
Tamron 35 - 135 mm lens	Installed, Operational
Sony PVM 1344Q Monitor	Installed, Operational
EG&G FT - 16 Turbine Flow Meter	Not Ordered
Omega Px - 303 Pressure Transducer	Not Ordered
4 RTD Temperature Transducers	Not Ordered
Borland C++	Installed, Operational
2" SCH. 40 PVC Pipe and Fittings	Not Ordered
Moore 42H - 100 Pressure Regulator	Received
2 Centrifugal Separators	Ordered
Liquid Crystal Paint	Samples Received