



High-temperature Calibration Facility for Calibrating Multihole Pressure Probes

N. Sitaram¹ · R. Sreekanth^{1,2} · Manoj K. Kalwan^{1,3} · C. Gajanan Tatpatti^{1,4}

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Abstract Design, fabrication, commissioning and validation details of an unique high-temperature calibration facility for calibrating multihole pressure probes such as five-hole probes at high temperatures are described in this paper. The facility has a capability to calibrate different pressure probes up to a maximum velocity of 6 m/s and up to a maximum temperature of 300 °C. The flow at the exit of the calibration facility is surveyed at different velocities and temperatures using a cooled combination probe with a Pitot tube and a thermocouple. The pressure and temperature are found to be uniform over a limited region but still useful for calibration of pressure probes. A large size five-hole probe with thermocouples is calibrated in the yaw and pitch angle range of $\pm 30^\circ$ using a computer-controlled calibration device at different velocities and temperatures. Representative calibration results are presented.

Keywords Five-hole probe · Combination probe · High temperature · Non-nulling calibration · Computer-controlled data acquisition system

Abbreviations

C_{PPITCH}	Pitch angle coefficient of the probe = $(P_T - P_B)/D$
$C_{PSTATIC}$	Static pressure coefficient of the probe = $(P - P_S)/D$
C_{PTOTAL}	Total pressure coefficient of the probe = $(P_O - P_C)/D$
C_{PYAW}	Yaw angle coefficient of the probe = $(P_L - P_R)/D$
D	Probe dynamic pressure (Pa) = $P_C - P$
P	Average pressure (Pa) = $(P_B + P_L + P_R + P_T)/4$
P_O	Total pressure (Pa)
P_B, P_C, P_L, P_R, P_T	Probe bottom, center, left, right and top hole pressures (Pa)
P_S	Static pressure (Pa)
Q	Probe dynamic pressure (Pa) = $P_O - P_S = P_O$ as $P_S = 0$
α	Yaw angle (Deg.)
β	Pitch angle (Deg.)

Introduction

Five-hole probes are extensively used for three-dimensional fluid flow measurements in turbomachinery and other aerodynamic flows. However, the probes are normally limited to low-temperature applications. For applications at elevated temperature, a thermocouple is added to the five-hole probe. Hence, temperature, pressure, velocity and flow angles can be measured. Such measurements are made in high-speed turbomachines as early as in 2002 [1].

✉ N. Sitaram
nsitaram.iitm@gmail.com

¹ Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

² Department of Mechanical Engineering, Vignan Institute of Technology and Science, Bhuvanagiri 508284, Telangana, India

³ Chiripal Industries Ltd., Ahmedabad 382405, India

⁴ Department of Mechanical Engineering, R. V. College of Engineering, Bengaluru 560059, India

Further developments are made in using commercially available small size fast response pressure transducers, Brouckaert et al. [2]. The sensor is water cooled and can be operated up to 200 °C. This water cooled probe is first used to measure total pressure in a high-temperature gas turbine environment, Mersinligil et al. [3]. The probe was also used to measure the variation of total pressure down stream of rotor 3 of a multistage high-speed compressor, Mersinligil et al. [4]. However, this methodology may not be suitable in other applications, for example for fire experiments. For such experiments, the probe has to be calibrated at different velocities to account for Reynolds number effects and different temperatures. Hence, a calibration facility where both temperature and velocity can be varied independently is to be developed to calibrate the probes at different temperatures and velocities (Reynolds number). This is the objective of the present investigation. However, it is very difficult to calibrate the five-hole probe manually at high temperatures. Because of high temperature, the location of the five-hole probe cannot change easily according to the requirements. Computer-aided automatic calibration of the five-hole probe is required. Because of the air in the calibration nozzle is at high temperature, it is not safe to change the calibration angles manually. A calibration device with step motors to change the probe yaw and pitch angles during calibration is required. Both the step motor rotation and data acquisition from the probe pressure tubes and thermocouples are to be controlled by a personal computer. To the authors' best of knowledge, only Schultz [5] had carried out such high-temperature calibration of a five-hole probe. However, the calibration range is limited. The present paper describes in sufficient details the design, fabrication, commissioning and validation of the high-temperature calibration facility. The paper also presents the details of calibration of the probe with the help of a computer-controlled calibration device. The yaw and pitch angles of the probe are varied by means of step motors, which are controlled by the computer and pressures and temperatures from the probe are acquired by the computer. To the best of the authors' knowledge, this type of calibration facility is unique. It is hoped these details will provide some help for other researchers in developing similar calibration facilities.

Design Details of the High-temperature Calibration Facility

Design Requirements

The design requirements of the facility are as follows:

Maximum velocity : 6 m/s Maximum temperature : 300°C

Flow and temperature should be uniform within 1% in at least an area of 10 × 10 cm, as the probe diameter would be at least 10 mm. It is also planned to carry out calibration up to ± 60° or more for improved design of multihole probes (7 or 9). This extended range is essential for measurements in fire experiments in enclosed chambers, where flow angles may vary substantially up to ± 60° from the probe reference direction. As the probe stem diameter near the probe tip is about 10 mm, the probe tip has to be away from the probe stem by at least 4 times the stem diameter to minimize the stem influence. Hence, the open jet has to be at least 20 × 20 cm to eliminate the influence of the jet edge. An area of 10 × 10 cm with uniform pressure, velocity and temperature is required for calibration. Hence, it is decided that the exit area of the nozzle should be 20 × 20 cm.

Design of Diffuser Section

During the design and installation of the calibration facility, many problems are encountered. As the space available is limited, the length of the diffuser section between heater box and settling chamber and the contraction section between settling chamber and calibration duct is very small. As this small length for diffuser causes flow separation, the diffuser is subdivided into many sections to minimize effective area ratio and divergence angle. Furthermore, the velocity in the heater box is small. To cause intense mixing of the high-temperature air, copper wool is placed at the exit of the heater box, whose size is reduced to increase velocity and better mixing. It is expected that both velocity and temperature in the calibration jet would be uniform within 1%.

Design of Heaters and Heater Control Circuits

A heater of about 100 kW power is required for the maximum velocity of 6 m/s and maximum temperature of 300 °C. However, to account for any loss in temperature from the heater box to the calibration nozzle, a heater bank consisting of four heater sub-assemblies of 35 kW each is installed in the box. Each of the four heater sub-assemblies has 35 individual heaters of 1 kW capacity. A tubular type heater is chosen, because of cost and ease of replacement of any damaged individual heater. Each of the heater sub-assemblies can be switched on/off to get the desired temperature. Furthermore, the power input (voltage) to the heater is supplied and controlled through a 110 kW variable speed drive (VSD) available in the laboratory, so that precise control of the temperature in the calibration jet is

possible. The facility is completely insulated from the heater inlet to the nozzle exit to avoid heat loss to the external air. Glass wool of 2" thickness is used with 1 mm Aluminum sheet over the glass wool. The control circuits to the heater are shown in Fig. 1.

Three stainless plates of dimensions 450 mm × 350 mm are placed at three different locations and are welded to the walls of the heater bank separating the four heaters, a gap 5 cm is left for the flow of air. This arrangement of baffles in between the heaters provides the time for the proper heating of air and produces airflow with uniform temperature. Photograph of the heater with baffles is shown in Fig. 2.

Four RTDs of different lengths are placed at gaps between the baffle and the heater bank walls in order to measure the temperature of the air after it passes through each heater so that the temperature of air can be monitored.

Design of Settling Chamber

From the above discussion, the size of calibration nozzle is chosen as 20 × 20 cm. As the length of the diffuser section is small, a contraction ratio of 25:1 is chosen. Hence, the size of the settling chamber is 1 m × 1 m. The length is chosen as 1.3 m to restrict the total length of the facility to a reasonable size. Screens and honeycomb are placed inside the settling chamber to reduce the turbulence level to about 1% and for flow and temperature uniformity. Static pressure taps are provided on the four sides of the settling chamber at the locations shown in Fig. 3. In addition, static pressure taps are provided on the calibration nozzle (not shown in Fig. 3).

Selection of Centrifugal Blower, Motor and VSD

The requirement of a velocity of 6 m/s in the calibration nozzle means a maximum gage pressure of 2 mm of water at ambient temperature and a gage pressure of 1 mm of water at a temperature of 300 °C. The mass flow varies from a minimum of 0.02 kg/s at a velocity of 1 m/s and at a temperature of 300 °C to a maximum of 0.28 kg/s at a



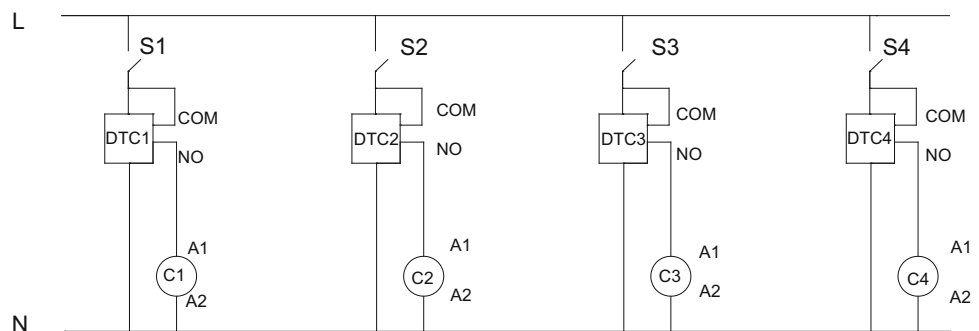
Fig. 2 Photograph of heater bank with baffles

velocity of 6 m/s and at ambient temperature. In addition, there is a large pressure drop in the heater bank, diffuser section, settling chamber and contraction. Hence, a blower with extremely small mass flow and large pressure rise is required. As a commercial blower of these specifications is not available, a blower with design specifications of 2 m³/s and 300 mm of water gage was selected and purchased. The speed of the blower and direct drive motor is chosen 1440 rpm to minimize vibrations and noise. A bypass duct at exit of the delivery duct allows to reduce mass flow substantially, but still with a large pressure rise. The speed of the motor, hence the blower speed can be controlled by 20 HP VSD.

Design of Calibration Device

A calibration device is fabricated to hold the five-hole probe and to change yaw and pitch angles of the probe for calibration. The calibration device is mounted on a table in front of the blower exit. It has an L-shaped bracket fitted with a screw to the table. This L-shaped bracket has two moving parts, one at upper part and the other one at the lower part. The upper part has a stepper motor with a through hole in the shaft. The probe is inserted in this hole during the calibration. A screw is fitted in the radial direction to the hole and is used to tighten the probe inside the hole. A circular scale with a range of 0°–360° with its center coinciding with center of the hole in which the probe is inserted is attached to the bracket. The probe can be rotated in both clockwise and anticlockwise directions to change the yaw angle with the help of a rotating

Fig. 1 Control circuit of the heaters



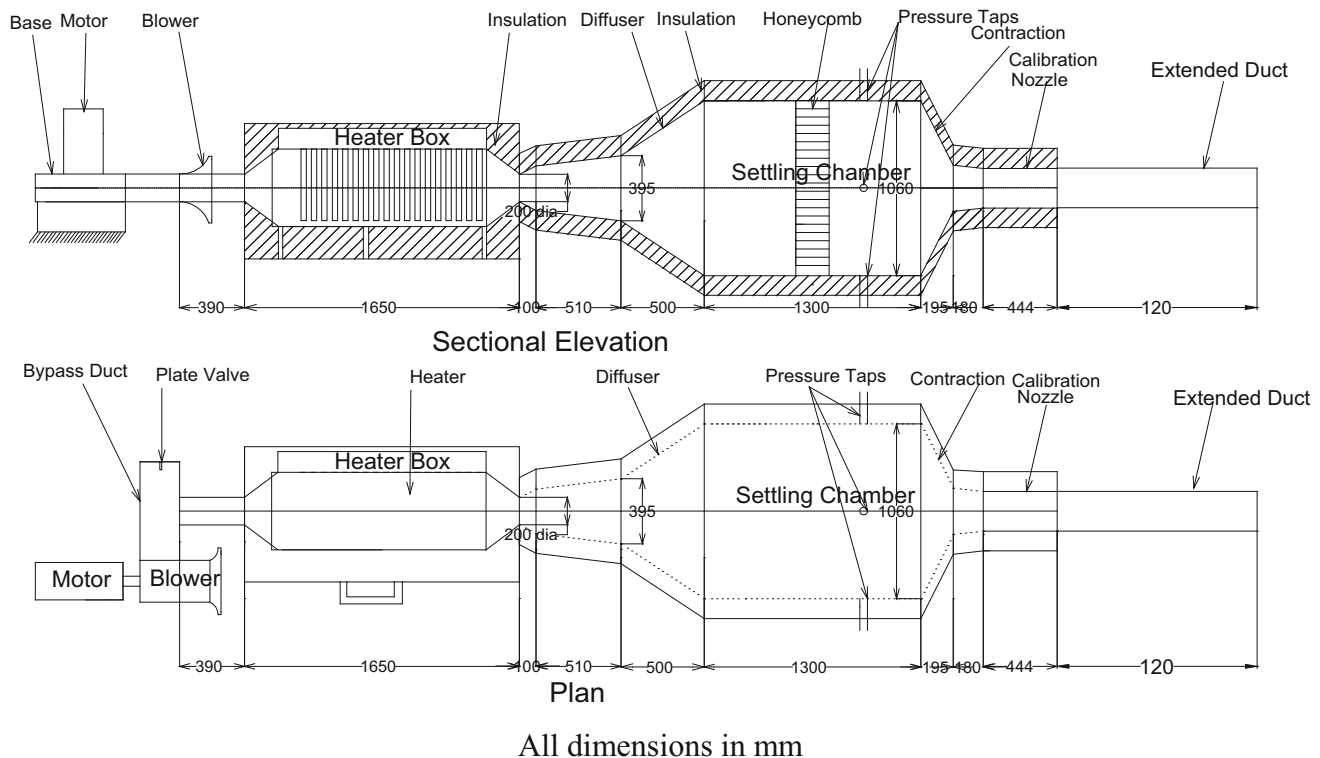


Fig. 3 Schematic of the high-temperature calibration facility (HTCF)

mechanism fitted onto the calibration device. The pitch angle of the probe is changed by rotating the L bracket about a vertical axis. The range of pitch angle possible on this device is from -70° to $+90^\circ$. This is very difficult to change the position of probe manually in front of high-temperature airflow. For this, two stepper motors are fixed to the calibration device. The stepper motors are controlled by a computer so that the position of probe can be changed according to the requirement. By automation of the calibration device, considerable time is saved and accuracy of the calibration data is improved. The Autocad drawing of calibration device is shown in Fig. 4. The calibration device with the cooled five-hole probe is shown in Fig. 9 (Item 6).

Design and Fabrication of Combination Probe with Thermocouple and Cooling Jacket

To measure the temperature profile at the exit of the nozzle of the calibration tunnel, a combination probe (900 mm length and 6.35 mm dia.) was designed and fabricated with a thermocouple embedded inside the probe tip. Inside the combination probe, two stainless steel tubes one of 2.75 mm dia. and other of 1.6 mm dia. are fitted. The thermocouple wire is inserted inside the 2.75 mm dia. tube to measure temperature. The 1.6 mm dia. tube is used to measure total pressure of flow. The head of the probe is

bent at 90° to face the flow at the exit of nozzle. By using this probe, flow can be measured at different velocities and different temperatures. To protect the probe from high temperature, a cooling jacket (about 750 mm long and 25.4 mm diameter) is designed and fabricated. The cooling jacket is fitted 10 cm away from the head of the combination probe. There are three stainless steel inlet tubes (750 mm long and 6.35 mm dia.) and three outlet tubes (700 mm long and 6.35 mm dia.) inside the cooling jacket. All joints of probe and cooling jacket are silver brazed to make them leak proof. Engine oil is circulated inside the cooling jacket to cool the probe. The cooling jacket is connected to a heat exchanger. The front and rear parts of the combination probe with the cooling jacket are shown in Fig. 5. The probe tip showing Pitot tube and thermocouple are shown in the inset on the top left of the figure. The design details of the cooling jacket, which is similar to that of the five-hole probe are presented in the section on five-hole probe.

Design and Fabrication of Traverse Mechanism

A traverse mechanism is designed and fabricated to hold and to traverse the combination probe horizontally and vertically. The traverse mechanism of the combination probe is designed for 200 mm traverse of the probe in horizontal and vertical axes. This traverse mechanism is

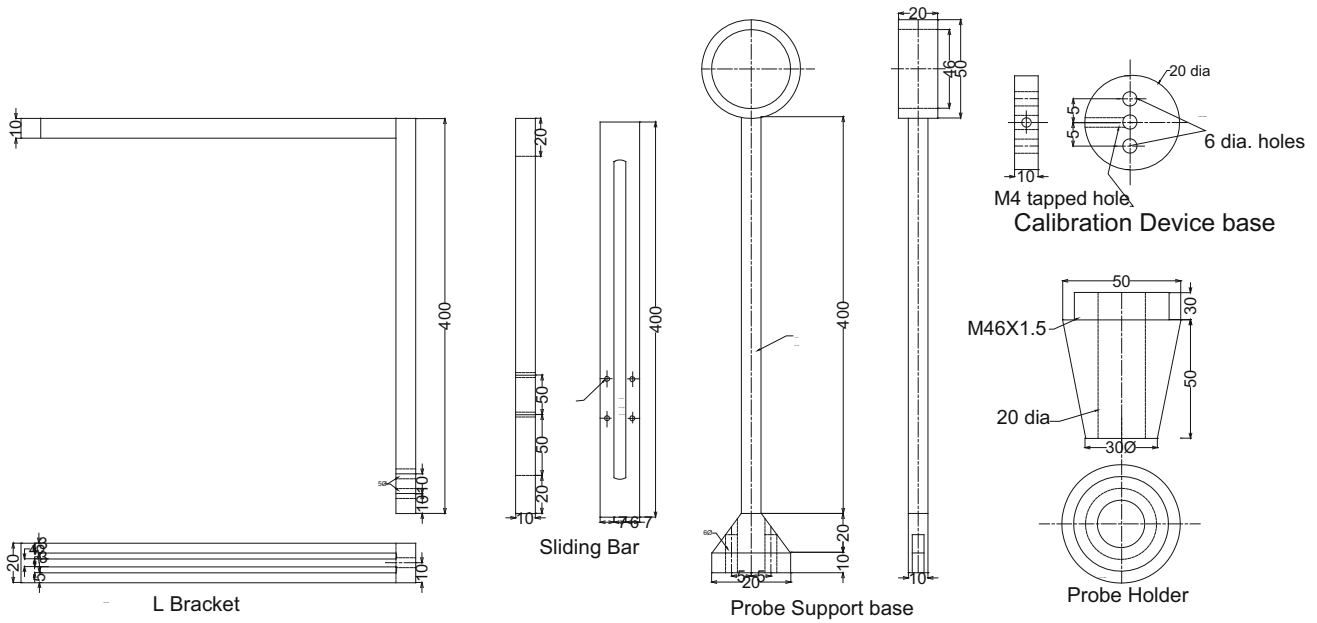
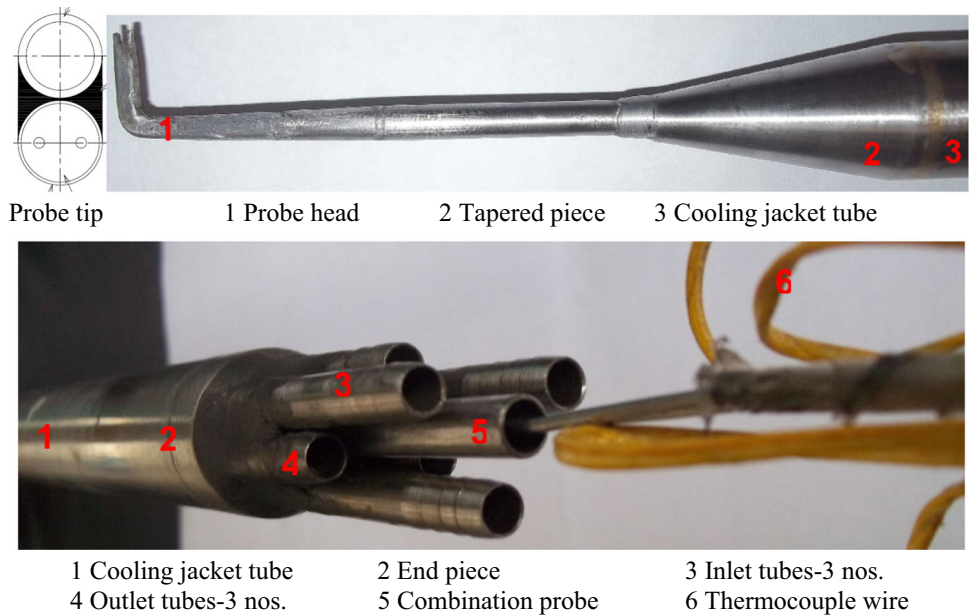


Fig. 4 Autocad drawings of components for calibration device

Fig. 5 Combination probe with cooling jacket



fitted on top of the exit nozzle, supported by a base plate. This traverse mechanism can be moved horizontally left and right side. To get the 200 mm traverse of probe, a 300 mm long, 50.8 mm square tube of 2.5 mm thick Aluminum square tube is used. The combination probe with the cooling jacket is fixed inside the threaded tube (26 mm inner diameter). This threaded tube can be traversed upward and downward with the help of a brass knurling nut. An Aluminum nut (50 mm OD, 25.5 mm ID and 50 mm long) is used to tighten the probe inside the threaded tube. Three screws are used to tighten the probe in

aluminum nut. The traverse mechanism along with the combination probe (Item 7) is shown in Fig. 9.

Design of Five-hole Probe

As the probe is to be used for fire experiments, where soot is likely to block the probe tubes, a probe of 9 mm overall diameter with five 3 mm diameter tubes is designed. Four ceramic insulators of 1.6 mm diameter with thermocouples are embedded in the probe at 90° apart. An Autocad drawing of the five-hole probe is shown in Fig. 6. The

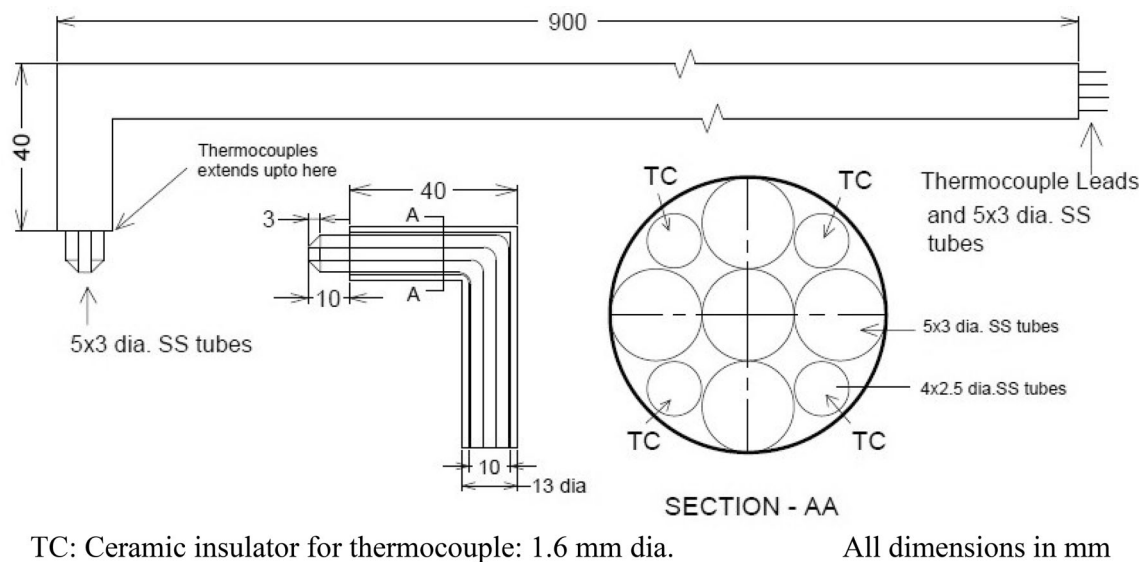


Fig. 6 Autocad drawing of five-hole probe

pressure tubes and thermocouples are inserted in a tube 13 mm outer diameter and 10 mm inner diameter.

Design and Fabrication of Cooling Jacket for Five-hole Probe

In fire chambers, the five-hole probe can be damaged due to high temperatures. To protect the probe from high temperatures, a cooling jacket (about 750 mm length and 38 mm diameter) is designed and fabricated for the five-hole probe. The cooling jacket is fitted 10 cm away from the probe tip. There are three stainless steel inlet tubes (700 mm length and 8 mm dia.) and three outlet tubes (750 mm and 8 mm dia.) inside the cooling jacket. All joints of the probe and cooling jacket are silver brazed to make them leak proof. Inside the cooling jacket engine oil is circulated to cool the probe. The cooling jacket is connected to a heat exchanger. The Autocad drawing of the cooling jacket for five-hole probe is shown in Fig. 7. The cooling jacket for the combination probe is very similar to the cooling jacket for the five-hole probe.

Cooling Arrangement

The cooling jackets of five-hole and combination probes are connected to a heat exchanger (Fig. 8). The engine oil is circulated between the cooling jacket and oil drum (2' dia. × 3' long). One oil pump is connected between the oil drum and cooling jackets to circulate the oil inside the cooling jackets of the probes. The oil pump pumps the cool oil from the oil drum to the cooling jacket. A 15 m long copper coil is fitted inside the oil drum for water flow with the help of a water pump. Water flows freely from the tap

which is connected to the water pump. Freely flowing water extracts heat from the circulating oil inside the drum and changes the oil temperature according to requirements. By using this cooling arrangement, the temperature of the combination and five-hole probes can be regulated and the probes can be protected from high temperature. The cooling arrangement is shown as Item 8 in Fig. 9.

Instrumentation

Hioki Memory HiLogger HIOKI Model 8430-20 Memory HiLogger is used for taking temperature and pressure transducer readings. Power to the HIOKI Memory HiLogger is supplied by Model Z1005 AC Adapter. The major features of the HiLogger are given as follows:

- Provides ten electrically isolated analog input channels for measuring voltage and temperature, plus four pulse-counting input channels. The isolated inputs alleviate constraints when measuring temperatures in live electrical circuits while minimizing interchannel interference.
- ms (millisecond) scanning of all channels provides rapid sampling capabilities. To meet the demand for measuring sudden changes in load, this model tracks waveforms that earlier 100 ms models could not track.
- CompactFlash card makes direct recording a snap for long-term data recording, transfer data to a PC via USB connection.
- Widescreen, bright LCD gives excellent view ability.

The HiLogger is shown as Item 9 in Fig. 9.

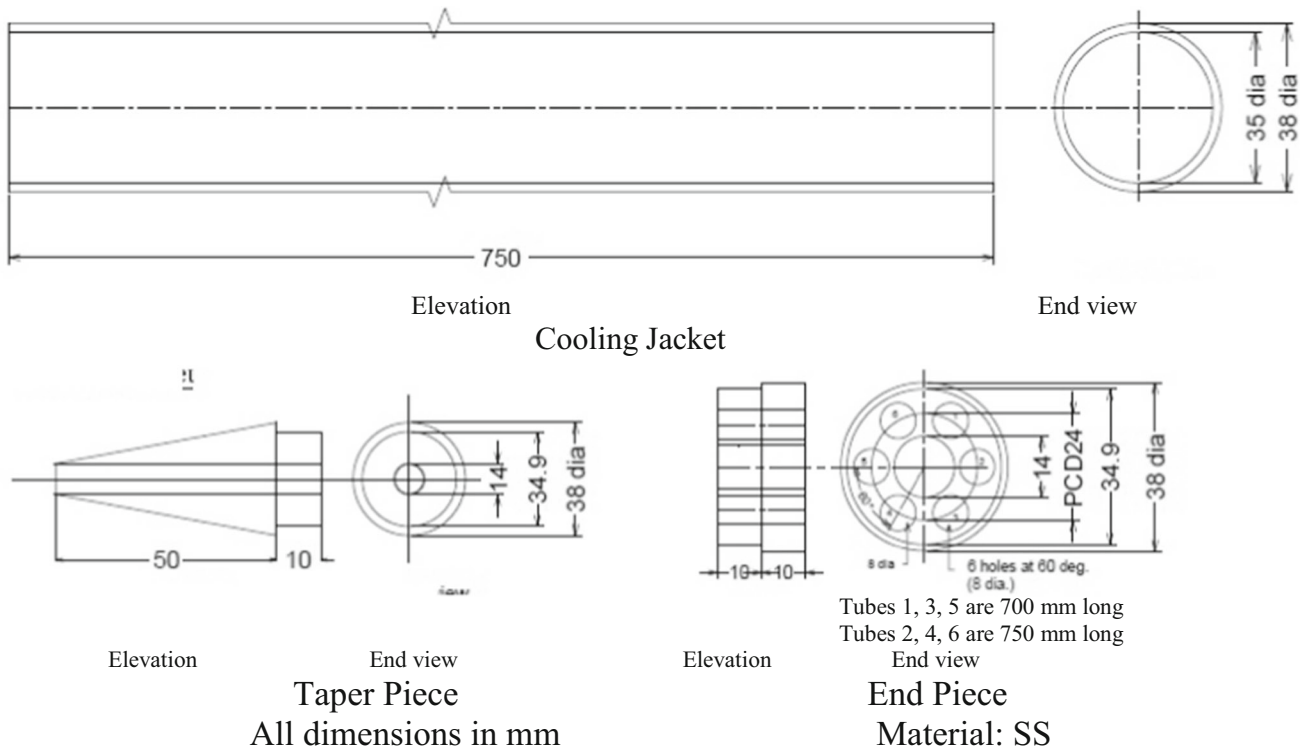


Fig. 7 Autocad drawing of cooling jacket for five-hole probe

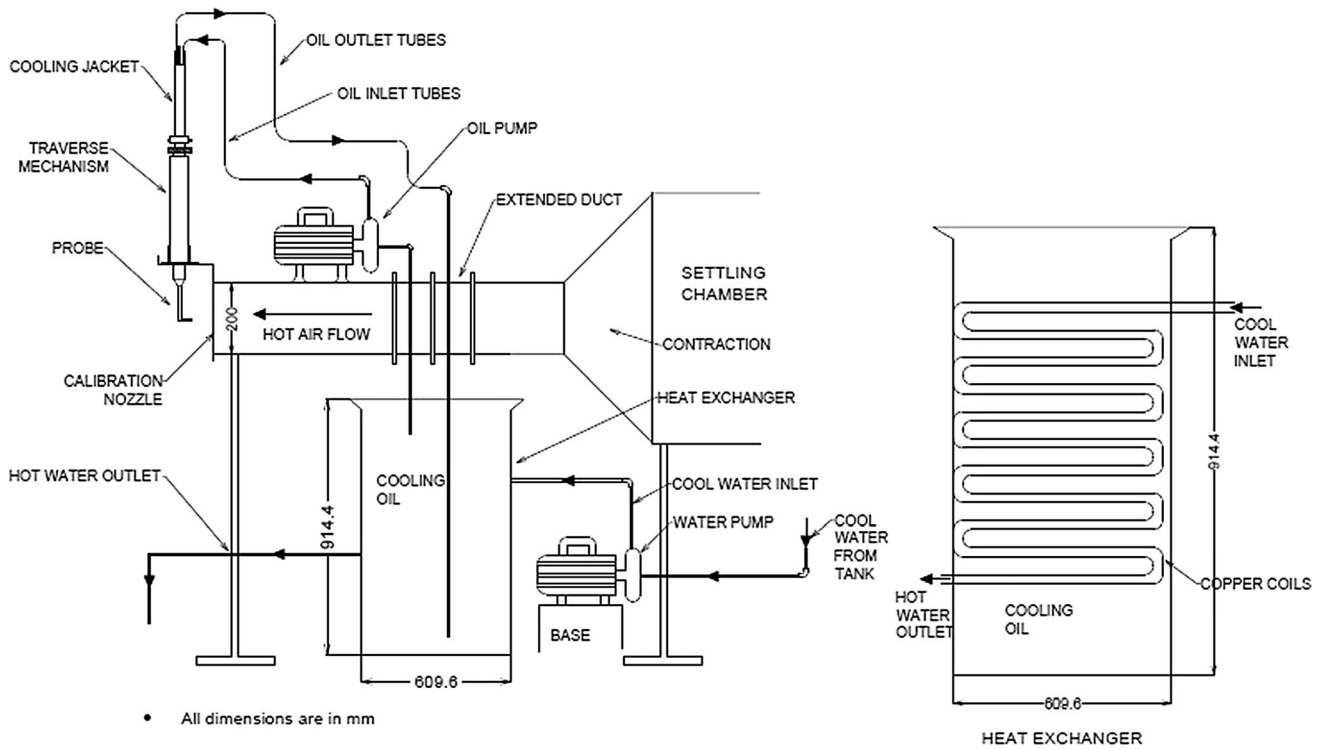


Fig. 8 Schematic of cooling arrangement

Fig. 9 Photograph of high-temperature calibration facility (HTCF)



- | | | | | |
|---|--|-------------------------|--------|------------------|
| 1 Centrifugal blower | 2 Heater | 3 Settling chamber | 4 Duct | 5 Extended ducts |
| 6 Five hole probe and calibration device | 7 Combination probe and traverse mechanism | | | |
| 8 Cooling arrangement | 9 Hioki memory logger | 10 Pressure transducers | | |
| 11 Temperature signal conditioning module | 12 Stepper motor controller | 13 Computer | | |

A photograph of the high-temperature calibration facility with all the components, probes and instrumentation is shown in Fig. 9.

Pressure Transducers

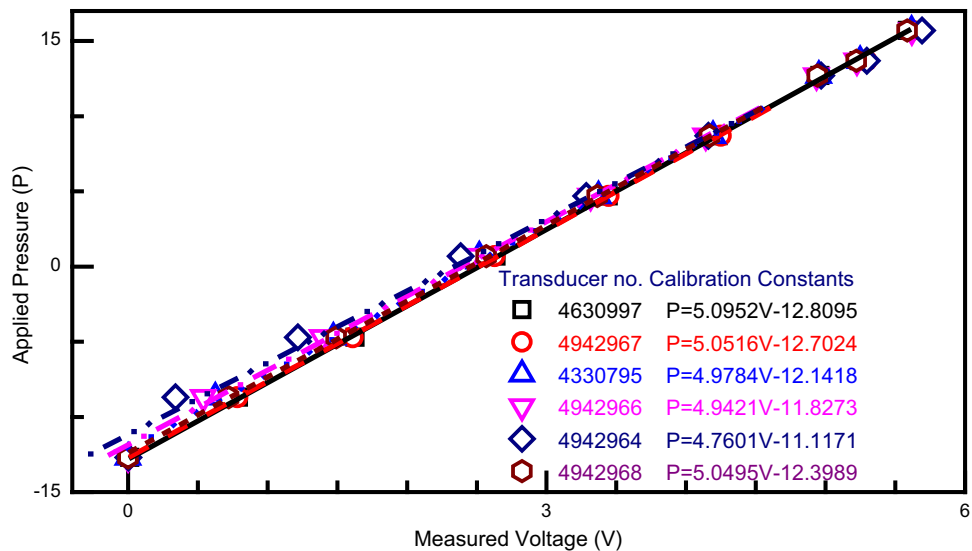
The six pressure transducers used in this experiment were made by Setra, Model 264, with a unidirectional output range 0–5 V, measuring ± 1.27 mm water gage (WG). The transducers were warmed up for a minimum of two hours prior to the conduct of the experiment. The 264 transducer is calibrated and requires no field adjustment. Generally, the mounting position has a zero shift effect on ranges below 1" WG. Whenever possible, any zero and/or span offsets should be corrected by software adjustment in the user's control system. However, both zero and span adjustments are accessible either on the front of the unit or by removing the optional conduit enclosure. The 264 transducers were calibrated in the vertical position. Calibration curves of the six pressure transducers are shown in Fig. 10. The calibration was done by applying known pressures and measuring the output voltage. These data are transformed into pressure versus voltage curves, so that the derived equations can be used to determine the pressure from the measured voltage. The calibration curves are

almost linear. The pressure transducers are shown as Item 10 in Fig. 9.

Computer-aided Calibration System

The computer-aided calibration system consists of the following components.

- A. *Computer-aided Calibration System Hardware Requirements:* The following hardware are required for the computer-aided calibration system:
 - A personal computer with the following minimum specifications:
 - CPU Intel Pentium IV 800 MHz or more with OS of Windows XP Home Edition.
 - 20 GB of free hard disk space, 1 GB RAM, USB ports: 3, PCI slot: 1
- B. *Computer-aided Calibration System Software Requirements* The following software are required for computer-aided calibration system:
 - NI Device driver LabView 2013 with runtime engine
 - Oriental motor driver software"soft_cc05if-usb_xp-v-_6-4zip"
 - CP210x_VCP_windows software for USB to serial converter

Fig. 10 Calibration curves of pressure transducers

- C. *Hardware connections* A block diagram showing the motor driver connection to the computer is shown in Fig. 11a. The connection diagram for Oriental step motor driver is shown in Fig. 11b. Figure 11c shows data acquisition device connection details.
- D. *Software Front Panel* Software front panel (Fig. 11d) has three tab controls: 1) initialization window, 2) parameter setting window and 3) controls and indicator window.
- E. *Software Installation* The software as given above is installed in the computer.
- F. *System Initialization* First the file path and file name in the box as shown in Fig. 11e are selected before running the program. Once the file path and file name are entered, device name for PCI card (By default Dev1 needs to be selected). Also, Visa name for data acquisition device (Check serial port, my computer → manage device → device manager-port) is selected as shown in Fig. 11f.
- G. *DATA Acquisition Initialization* The data acquisition system is initialized and the front panel shows a message as in Fig. 11g. If system initialization (Fig. 11h) is failed and any of the temperature or pressure LEDs are in RED (as in Fig. 11i), the connections need to be checked and the program is to be restarted.
- H. *Parameter Setting* Once the system is initialized, the required parameters, such as acquisition time, yaw and pitch angles and their intervals need to be set as shown in Fig. 11j. Once parameters are set, data acquisition starts automatically and the data is stored in an Excel sheet in the file path mentioned in the file path block.
- I. *Controls and Indicators* The position of the motor and the pressure and temperature sensor data are in this tab (Fig. 11k).
- J. *Report* The report can be opened by going to the path in the step System Initialization (Fig. 11l). For example: C:/Documents and Settings/user/Desktop/ Home_automation_project/Data. The file can be selected and double clicked to open.

Results and Discussion

Flow and Temperature Uniformity in the Calibration Zone at Different Velocities and Temperatures

The objective of the present investigation is calibration of the five-hole probe at different temperatures and velocities. It is important to establish uniform temperature and pressure zone where the probe can be calibrated. A combination probe (Item 7 in Fig. 9) which can be traversed in both horizontal and vertical directions with the help of a traverse mechanism is used to measure the pressure and temperature at the exit of the calibration nozzle. The experiments were carried out at ambient temperature, 70 °C, 100 °C and 150 °C temperatures for velocities of 5 m/s, 3 m/s, 2 m/s. Because of certain problems with the VSD, the maximum temperature obtained is 150 °C only. For the sake of brevity, only a few representative surveys are shown in Fig. 12.

The temperature contours at ambient temperature and at 5 m/s are shown in Fig. 12. The temperature at ambient temperature and 5 m/s is uniform at almost everywhere except at the corners. The region in which temperature is uniform is good enough to calibrate the five-hole probe.

The non-dimensional pressure contours at ambient temperature and at 5 m/s with baffles in between the heaters at the exit of the calibration nozzle are shown in

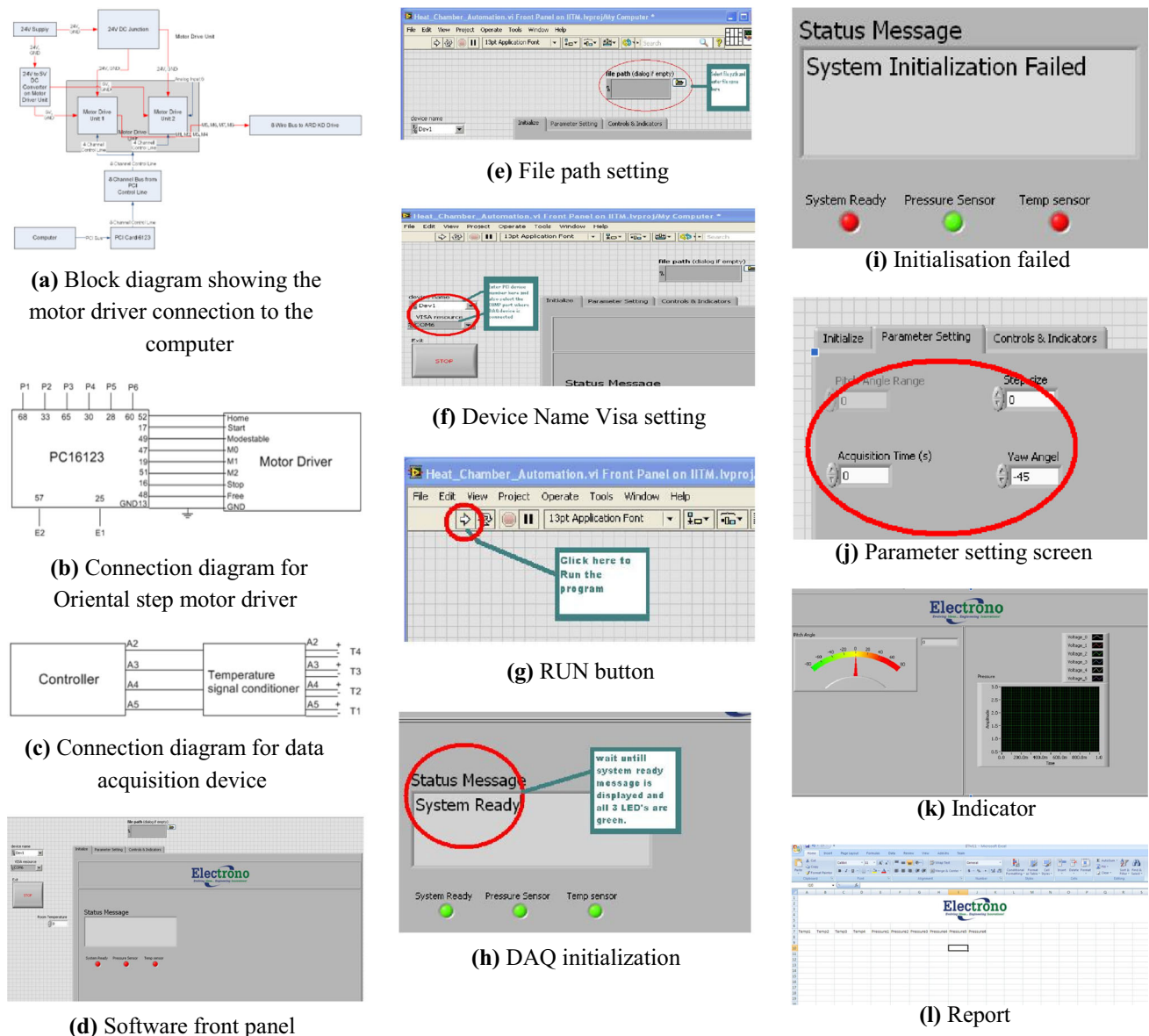


Fig. 11 Details of computer-controlled data acquisition system

Fig. 12. The pressure contours are not uniform, however, there are some region in which pressure is uniform. This region can be identified as 5 to 15 cm from the left of the calibration nozzle in the horizontal direction and 1 to 7 cm from the bottom of the calibration nozzle in the vertical direction. The pressure in the center is lower than the pressure in top and bottom of the calibration zone. The baffles introduce pressure loss in the center.

The temperature contours at 150 °C and at 5 m/s are also shown in Fig. 12. The extent of uniform temperature is reduced compared to the case of ambient temperature and 5 m/s but still sufficient for the calibration of the five-hole probe.

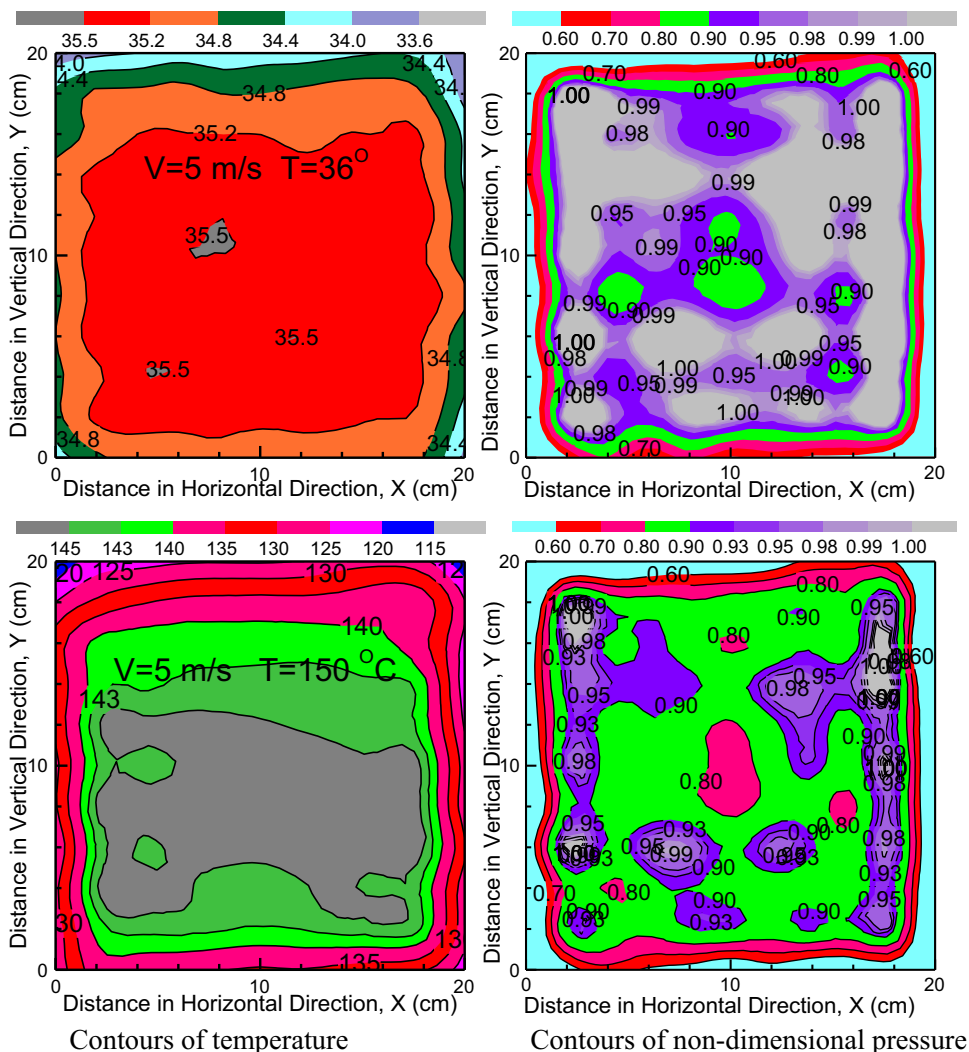
The non-dimensional pressure contours at 150 °C and at 5 m/s are shown in Fig. 12. From the contours, it is evident

that the pressure is uniform in lower half within 1% in a limited zone. This region can be identified as 6 to 14 cm from the left of the calibration nozzle in the horizontal direction and 1 to 7 cm from the bottom of the calibration nozzle in the vertical direction. The pressure is not uniform in the upper half region. The pressure in the center is lower than the pressure in top and bottom of the calibration zone. The baffles introduce pressure loss in the center.

Calibration of the Five-hole Probe at Different Velocities and Temperatures

The five-hole probe with thermocouples and cooling jacket was calibrated at the exit of the high-temperature calibration facility of Fluid Systems Laboratory, Department of

Fig. 12 Contours of pressures and temperatures at different temperatures and velocities



Mechanical Engineering, IIT Madras. It was fixed at the exit of the tunnel, so that the tip of the probe was in the center of the uniform temperature and pressure region, just at the exit of the tunnel. The stem was clamped in a calibration device which rotates the probe about yaw and pitch axes at 10-degree intervals. Special care was taken that the tip of the probe did not come too close to the walls of the tunnel in order to ensure the probe is always in the uniform pressure and temperature zone. The reference temperatures and pressures of the flow were continuously monitored with the combination probe which was also fixed in front of the exit of the tunnel several times at different points across the opening before the calibration to ensure stable and uniform conditions.

The calibration of probe was carried out at ambient, 70 °C, 100 °C, 150 °C temperatures and at 2 m/s, 3 m/s, 5 m/s velocities in order to study the effect of temperature and Reynolds number on the pressure coefficients. However, for the sake of brevity, only sample results are presented in Figs. 13 and 14.

For operation in the non-nulling mode, it is apparent that the calibration characteristics must include data that represent pressure differences in both the pitch and yaw planes, as well as differences between measured and true local total and static pressures. The pressure coefficients representing these data must be defined so that they are independent of velocity and are a function only of the flow angularity. Krause and Dudzinski [6] found that an indicated dynamic pressure formed by the difference between the indicated total pressure, P_C , and the averaged value of the four indicated static pressures, P_L , P_R , P_B and P_T , was a satisfactory normalizing parameter and this normalizing parameter reduced the scatter in the calibration data as compared to using the true dynamic pressure. This is convenient, since using the true dynamic pressure would have introduced an unknown quantity. Since then other researchers working with five-hole probes used similar non-dimensional calibration coefficients. The four calibration coefficients are defined as follows:

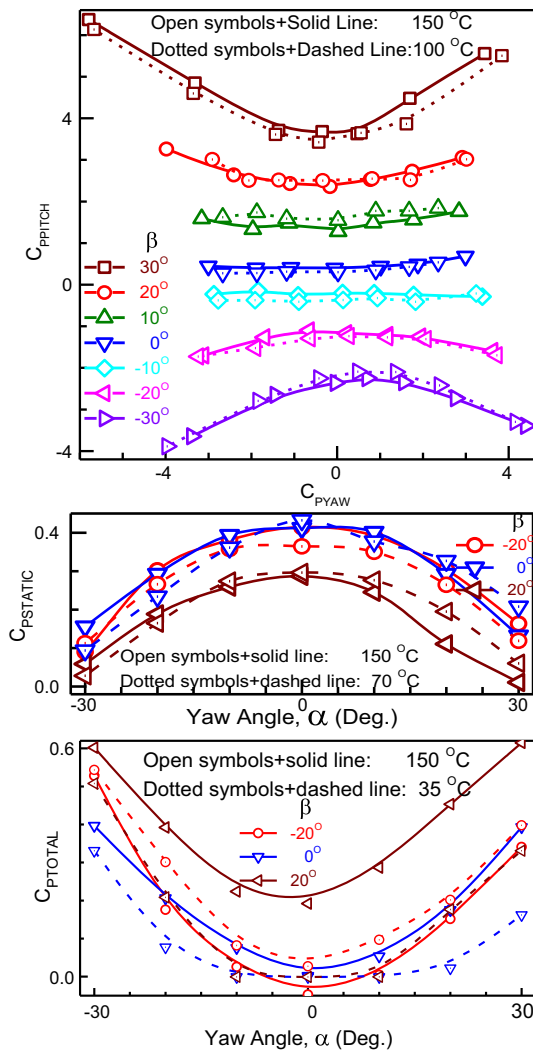


Fig. 13 Comparison of calibration curves at 5 m/s and at different temperatures

$$P = (P_L + P_R + P_T + P_B)/4 \quad D = (P_C - P)$$

$$Q = P_O - P_S = P_O \text{ as } P_S = 0$$

$$C_{PYAW} = (P_L - P_R)/D \quad C_{PSTATIC} = (P - P_S)/Q = P/P_O$$

$$C_{PPITCH} = (P_B - P_T)/D \quad C_{PTOTAL} = (P_O - P_C)/$$

$$Q = (P_O - P_C)/P_O = 1 - P_C/P_O$$

Effect of Temperature on Calibration Curves

To study the effect of temperature, the C_{PPITCH} vs. C_{PYAW} , $C_{PSTATIC}$, C_{PTOTAL} curves for various values of yaw and pitch angles at two different temperatures and same velocity are presented.

Calibration data at velocity 5 m/s are shown in Fig. 13. The calibration curves C_{PPITCH} vs. C_{PYAW} at different values of yaw and pitch angles are shown. At moderate yaw angles, C_{PPITCH} is a linear function of pitch angle; similarly, at moderate pitch angles, C_{PYAW} only varies

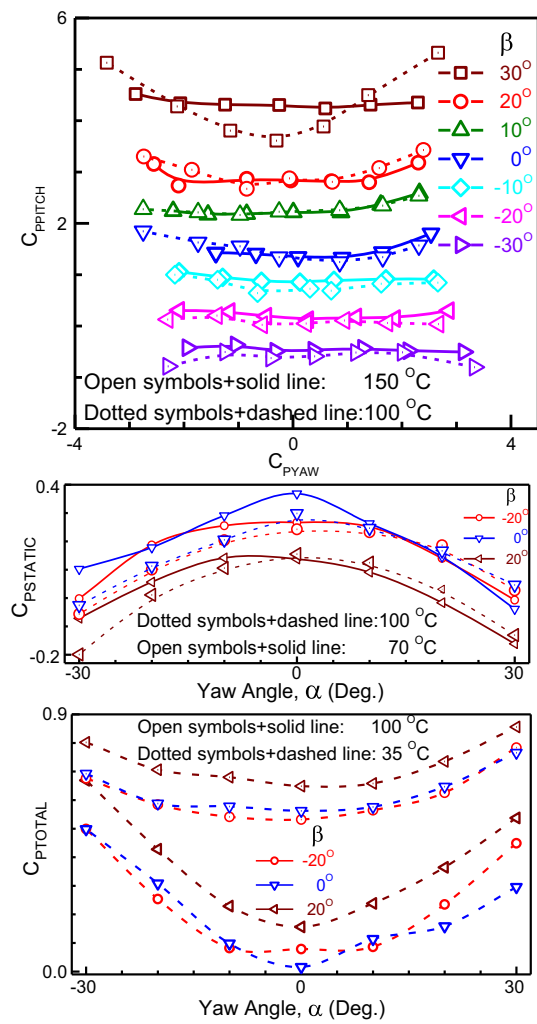


Fig. 14 Comparison of calibration curves at 3 m/s and at different temperatures

linearly with yaw angle. However, for the pitch and yaw angles more than 15°, the pressure response is nonlinear and stronger coupling between pitch and yaw angles can be observed. C_{PPITCH} vs. C_{PYAW} plots at 5 m/s at both temperatures (150 °C and 100 °C) are almost identical.

The static and total pressure coefficients at different values of α and β are also shown in Fig. 13. When $\alpha = 0$ and $\beta = 0$, the central hole measures the total pressure of the flow, therefore, C_{PTOTAL} is nearly zero at small values of α and β as expected. The stagnation point departs from the central hole as α and β increase, thereby decreasing the averaged surface pressure of the four side holes. Hence, it has a maximum when the probe is aligned with the flow. This maximum value depends on the probe geometry. When the yaw and pitch angles increase, the pressure on the windward hole increases whereas the pressure on the leeward hole decreases, thereby decreasing $C_{PSTATIC}$. The calibration curves of $C_{PSTATIC}$ at two different temperatures (150 °C

and 35 °C) follow the same trend but as positive α and β angles increase there are some differences.

Calibration data at velocity 3 m/s are shown in Fig. 14. Figure 14 shows the calibration curves of C_{PPITCH} vs. C_{PYAW} , at different values of α and β angles. At moderate values of pitch and yaw angles, C_{PPITCH} is a linear function of pitch angle but at larger pitch angles and at the larger yaw angles there variation due to the effect of Reynolds number as it changes with temperature. Similarly, at moderate pitch angles, C_{PYAW} only varies linearly with yaw angle. However, for the pitch and yaw angles larger than 15°, the pressure response is nonlinear and stronger coupling between pitch and yaw can be observed. The comparative graph of C_{PPITCH} vs. C_{PYAW} at 3 m/s at two temperatures (150 °C and 100 °C) is almost identical except for a small deviation at larger values of α and β angles.

The static pressure coefficients at temperature of 100 °C and 70 °C and total pressure coefficients at temperature of 100 °C and 35 °C at different values of α and β are shown in the figure. The C_{PTOTAL} curves at both temperatures follow same trend but the deviation in the values is high. The comparative graph of $C_{PSTATIC}$ at two different temperatures follows the same trend but as positive α angle increases there is more deviation.

Conclusions

The paper presents details of design, development, commissioning and validation of a high-temperature calibration facility. The facility can be used for calibrating multihole probes up to a velocity of 6 m/s and 300 °C. The paper also presents design and fabrication of two cooled probes for use in the facility. A cooled combination probe with a Pitot tube and a thermocouple to measure pressure and temperature at the exit of the calibration nozzle to establish uniform pressure and temperature for calibrating a cooled five-hole probe is designed and fabricated. A cooled five-hole probe with four thermocouples is also designed and fabricated.

A computer-controlled data acquisition system which controls the motion of the step motors for changing the five-hole probe calibration yaw and pitch angles and to acquire pressure and temperature data from the five-hole probe is also developed.

The paper provides sufficient details of the high-temperature calibration facility, probes and data acquisition system so that other interested researchers can develop similar facilities for their research.

The pressure and temperature in the calibration region are found to be uniform over a limited region but still useful for high-temperature calibration of pressure probes.

The cooled five-hole probe is calibrated in the yaw and pitch angle range of $\pm 30^\circ$ at four temperatures viz., ambient (35 °C), 70 °C, 100 °C and 150 °C and three velocities, viz., 5, 3 and 2 m/s. The effect of temperature on the calibration curves is found to be small.

The facility can be modified to work as high-temperature cascade facility with a cooled nozzle vane as a test article. A miniature (3 mm dia.) cooled five-hole probe based on the design of the probe described in this paper can be developed and used for flow and temperature measurements in the high-temperature cascade facility.

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Declarations

Conflicts of interest The authors declare that they do not have any conflicts of interest or competing interests in publishing this paper.

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