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(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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Calibration of multi-hole probes for measurements in compressible organic vapor flows

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ABSTRACT

Multi-hole probes are necessary devices to measure flow characteristics and losses in turbomachinery. The present contribution reports the first experience with calibrating and using multi-hole probes in high-speed flows of the organic vapor Novec 649 at elevated pressure and temperature levels. It is found that the classical scheme, established for perfect gas applications, must be extended by an additional quantity reflecting the impact of the initial thermodynamic state on the pressure signals and the data reduction. The practical use and operational issues of three- and five-hole probes for ORC-turbomachinery research are discussed based on the new results. A promising hybrid experimental-numerical calibration approach significantly reduces the tremendous calibration effort.

1 INTRODUCTION

Multi-hole probes for measuring flow angles and Mach numbers have long been used in turbomachinery applications working with perfect gas. Although powerful optical or thermal flow measurement techniques are now available, pneumatic probes are still the only approach for determining losses in turbomachinery. Whereas the calibration of multi-hole probes and the data reduction is relatively straightforward in incompressible flow (see, for instance, Hall and Povey (2017)), substantial efforts are required for compressible flows. The significant increase in calibration efforts is caused by the need to include the Mach number M as a relevant similarity number for compressible flows. Main et al. (1996) used a pseudo-Mach number coefficient C_M as an additional dimensionless parameter in addition to the pitch, yaw, and total pressure coefficients. Johanson et al. (2001) proposed a calibration scheme based on probe sectors, and Bachner et al. (2022) considered probes with base pressure holes for transonic flow applications. Due to the decreasing sensitivity regarding the pseudo-Mach number coefficient, this flow regime is particularly challenging.

To utilize multi-hole probes for investigations of the flow through cascades for organic Rankine cycle (ORC) turbines, some specific challenges must be considered. Firstly, the potential problem of condensation of the organic vapor requires special attention for pneumatic measurement systems, see Conti et al. (2022). Furthermore, the complex thermodynamic behavior of the isentropic flow relations always requires additional efforts in data reduction for organic vapors, as Schollmeier and aus der Wiesche (2022) discussed for Pitot probes.

In addition to the well-known challenges for multi-hole probe calibration in compressible flows of perfect gases, a completely new problem enters when non-ideal compressible fluid dynamics (NICFD) are considered. In NICFD, the pressure ratios and multi-hole probe coefficient behavior depend on the inlet or initial total state of the fluid. Whereas universal isentropic relations exist for a perfect gas utilizing the isentropic exponent γ, these relations become functions of the initial thermodynamic state in the case of non-ideal gas dynamics. Considering a van der Waals model, Tsien (1946) predicted this specific NICFD feature, and Spinelli et al. (2018) reported evidence for this phenomenon in experiments with expanding flows of siloxane in a Laval nozzle. For compressible flows, the data reduction process of pneumatic probes rests largely on isentropic relations. Thus, the probe calibration maps or calibration spaces for multi-hole probes applied to organic vapor flows have to consider, in principle, the initial thermodynamic state. They are not generally independent of initial thermodynamic states, as in the case of a perfect gas. No information is available in the literature on how relevant this specific NICFD phenomenon would be for multi-hole probe data reduction. It might be argued that this NICFD feature might not affect all flow quantities similarly. For instance, the flow angle determination might be less influenced by the initial thermodynamic state as the static pressure measurement.

So far, only Pitot probes, and not multi-hole probes, have been employed for organic vapor flows (e.g., Baumgärtner (2020), Reinker et al. (2021), Conti et al. (2022), aus der Wiesche (2023)). Therefore, more information about calibrating and applying multi-hole probes in compressible organic vapor flows is needed. Their use is essential for determining ORC turbine cascade loss and investigating complex flow phenomena.

2 FUNDAMENTALS OF MULTI-HOLE PROBES

The fundamentals of multi-hole probes can be illustrated by considering a typical five-hole probe schematically shown in Figure 1 with its hole numbering (the reader will quickly transfer the following relations to three-hole probes). Figure 1 also shows the two probe designs investigated in this study.

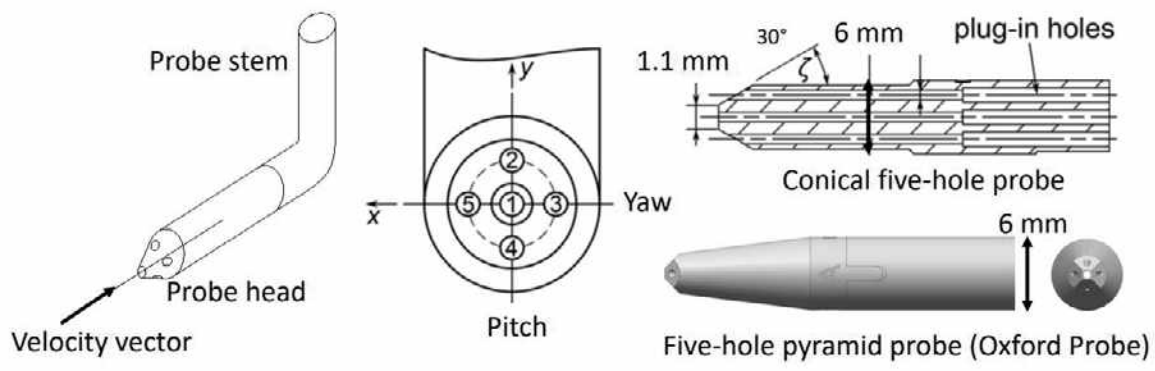

Figure 1: Schematic of a five-hole probe, hole numbering convention, and the study's probe designs

Adopting the definition used by Passmann et al. (2021), the pitch and yaw, and total pressure coefficients are

$$C_\alpha = \frac{p_2 - p_4}{p_{dyn}^*} \quad \text{and} \quad C_\beta = \frac{p_5 - p_3}{p_{dyn}^*} \quad \text{and} \quad C_{pt} = \frac{p_t - p_1}{p_{dyn}^*} \tag{1}$$

with the pseudo-dynamic pressure $p_{dyn}^* = p_1 - p_{avg}$ and $p_{avg} = (p_2 + p_3 + p_4 + p_5)/4$. Here, p_{dyn}^* is called a pseudo-dynamic pressure since p_1 and p_{avg} are close to the total and static pressures for flow-aligned probes ($\alpha = \beta = 0$) but deviate significantly if the flow is at incidence. It should be noted that alternative definitions for p_{avg} are sometimes used as discussed by Hall and Povey (2017).

To account for compressibility effects, a Mach number coefficient (sometimes called the pseudo-Mach number for the same reasons) is used according to Main et al. (1996)

$$C_M = \sqrt{\frac{2}{\gamma - 1}\left(\left(\frac{p_1}{p_{dyn}^*}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)}. \tag{2}$$

In the case of organic vapor, the choice of the value of the isentropic exponent γ is, in principle, not free of difficulties (see Schollmeier and aus der Wiesche (2022)). However, C_M only represents a calculation quantity, not the actual Mach number. In this study, the Mach number coefficient (2) is evaluated using the specific heat ratio γ at the actual stagnation state of the working fluid.

The pressure distribution measured at the probe tip determines the calibration coefficients. Dimensional analysis shows that for the compressible flow of a perfect gas, a probe flow quantity is a function of the angles α and β, the Reynolds number Re, the Mach number M, and the isentropic

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exponent γ. The Reynolds number dependency vanishes for sufficiently high probe Reynold numbers (Passmann et al. (2021a)). This condition is typically fulfilled in high-speed flows of organic vapors. However, an additional dimensional similarity number X is necessary to account for real gas effects in non-ideal compressible flows (see aus der Wiesche and Reinker (2022). Thus, for a five-hole probe, the three-dimensional calibration space $\{\alpha, \beta, M\}$ must be extended to a four-dimensional hyperspace $\{\alpha, \beta, M, X\}$ in the case of organic vapor flows. The need to introduce this additional similarity number X is directly related to the problem of the impact of the initial thermodynamic state, as discussed above. So far, no standard for X has been established, although sometimes the compressibility factor Z or the fundamental derivative of gas dynamics Γ are considered additional similarity quantities. Without an appropriate definition of X, the calibration of multi-hole probes has to account for the stagnation temperature T_t and pressure p_t (i.e., the temperature and pressure in the settling chamber of the wind tunnel). The stagnation conditions represent the initial thermodynamic state in the present wind tunnel experiments. The subject of the present study is to investigate how relevant the inlet state is for an actual multi-hole probe calibration for organic vapors.

3 EXPERIMENTAL AND NUMERICAL METHOD

The experimental study was conducted in the closed-loop organic vapor wind tunnel facility CLOWT calibration test section at Muenster University of Applied Sciences. General technical details about CLOWT are provided by Reinker et al. (2021, 2021a) and Hake et al. (2022). Figure 2 shows the wind tunnel schematically (without an electrical heating system and thermal insulation) and the calibration test section in more detail. The working fluid was Novec 649 by 3M. Selected thermodynamic properties of Novec 649 are listed in Table 1.

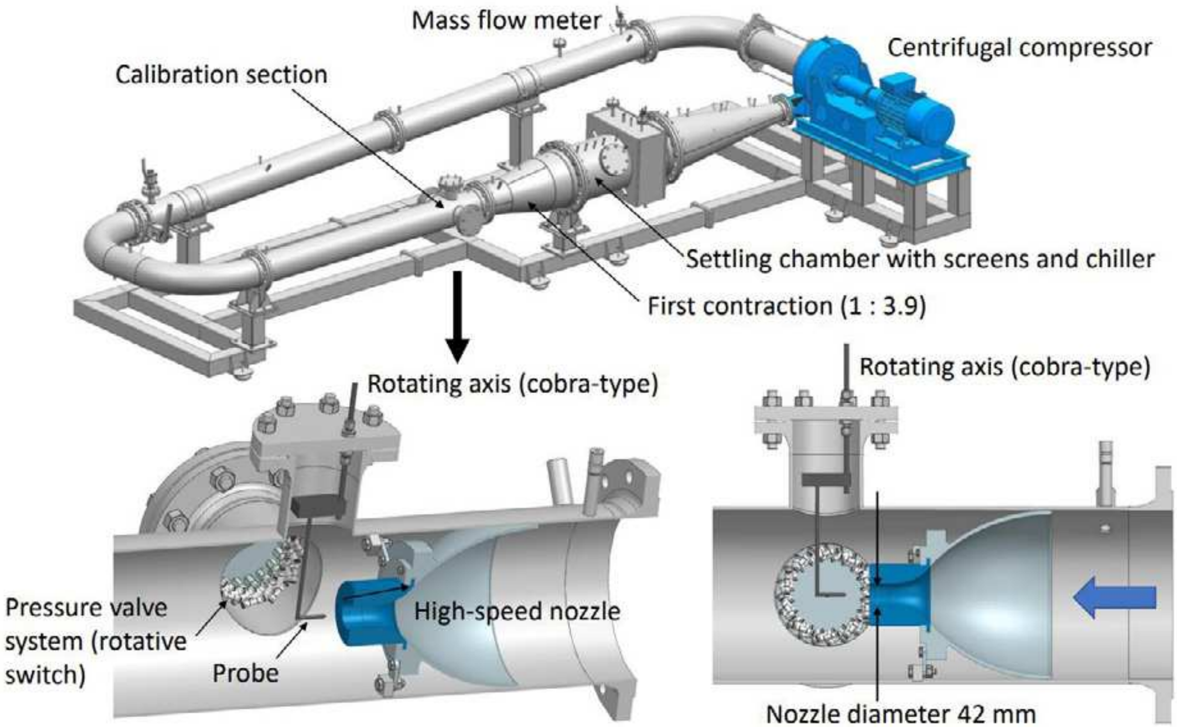

Figure 2: Test facility CLOWT and details of the calibration test section

Table 1: Thermodynamic properties of Novec 649 (after REFPROP by NIST)

Chemical Formula	Molecular Mass	Critical Pressure	Critical Temperature
$CF_3CF_2C(O)CF(CF_3)_2$	316 g/mol	1.88 MPa	442 K

The multi-hole probes were calibrated inside the calibration chamber's free jet (diameter 42 mm). The yaw angle β of the probes could be continuously varied by a cobra-type mechanism shown in Figure 2. The pitch angle α was fixed during a yaw-angle variation. The organic vapor was driven by a centrifugal compressor with variable running speed, controlling the calibration Mach number M. The total or stagnation pressure p_t and the total temperature T_t were recorded in the settling chamber. The vapor flow was accelerated to transonic speeds in a two-stage contraction zone. The static pressure p was measured at the exit of the high-speed nozzle and in the calibration chamber. In an initial set of measurements, the inflow turbulence level was determined by hot-wire anemometry to be Tu = 0.2 % up to 1.0 % at higher Mach numbers.

Before the multi-hole probe calibration, Pitot probe measurements were carried out in the free jet to verify the assumption of an isentropic nozzle expansion. The approach described by Reinker et al. (2021) and Hake et al. (2022) was employed for all pressure measurements to prevent potential measurement errors due to condensation. In this approach, all pressure lines were placed inside the heated wind tunnel, and a rotative mechanism switched the valves to the pressure transducer (see Figure 2). During the calibration, the total temperature was controlled by the chiller and the electrical heating system. The mass flow rate was measured independently in the return of the wind tunnel enabling an accurate determination of the Mach number. The amount of mass filled in the closed wind tunnel determined the density level and hence the Reynolds number Re.

The present study considers two probe designs shown in Figure 1 (right). The conical five-hole probe had the advantage that its body obeyed cylindrical symmetry, making the numerical calibration viable (see the following section and Passmann et al. (2021). In addition, the so-called Oxford Probe design (Hall and Povey (2017)) was considered, too. The Oxford Probe design is based on a truncated pyramid body with flow separation and probe sensitivity advantages. Using this pyramid body, the behavior of an original five-hole probe and a three-hole probe was investigated in the experiments with Novec 649 at two different operation conditions listed in Table 2. The two experimental cases (HD and LD, see Table 2) are shown as black dots in the T,s-diagram of Figure 3.a, too. The probe Reynolds numbers $Re = \rho Ud/\mu$ with the probe diameter d and inflow velocity U was of order $Re = 5 \times 10^4$ up to 8×10^5 (with an uncertainty level of 2 – 5 %). For such a high probe Reynolds number level, the sensitivity against Reynolds number can be neglected, as Passmann et al. (2021a) discussed. Using a Laval nozzle, a maximum Mach number level of M = 1.2 could be achieved in CLOWT, but severe probe stem vibrations occurred for Mach numbers above 0.86. To avoid a destruction of the probe, the calibration was hence restricted to a maximum Mach number of about M = 0.84. 46

Considering precision and bias errors, the total uncertainty levels listed in Table 3 were achieved for the relevant quantities (see also Reinker et al. (2021a)). Due to the temperature control system, the temperature drift was of order 10^{-3} K/s for a constant compressor running speed, but slightly different temperature levels T_t occurred for different running speeds. Hence, the nominal total temperature levels for the calibration cases, see Table 2) were not precisely achieved for all running speeds during the experimental campaign, and systematic temperature level deviations of order 1 K existed. The nominal total specific enthalpy was nearly identical for the two experimental cases listed in Table 2 (h_t = 391.5 kJ/kg and 390.0 kJ/kg, respectively).

Table 2: Nominal operation conditions for the experimental probe calibration with Novec 649

Case	**Density ρ_t**	**Pressure p_t**	**Temperature T_t**	**Compressibility Factor Z**	**Fundamental derivative Γ**
High-density HD	26.9 kg/m^3	2.44 bar	378 K	0.91	0.93
Low-density LD	16.2 kg/m^3	1.51 bar	375 K	0.95	0.97

Table 3: Experimental measurement uncertainty levels (typical values)

Pressure $\Delta p/p$	**Temperature $\Delta T/T$**	**Mach Number $\Delta M/M$**	**Angle $\Delta\beta$**	**Coefficients $\Delta C/C$**
0.6 % up to 1.0 %	$\leq$ 0.1 %	1.0 % up to 4.0 %	$\leq$ 1°	$\leq$ 3 %

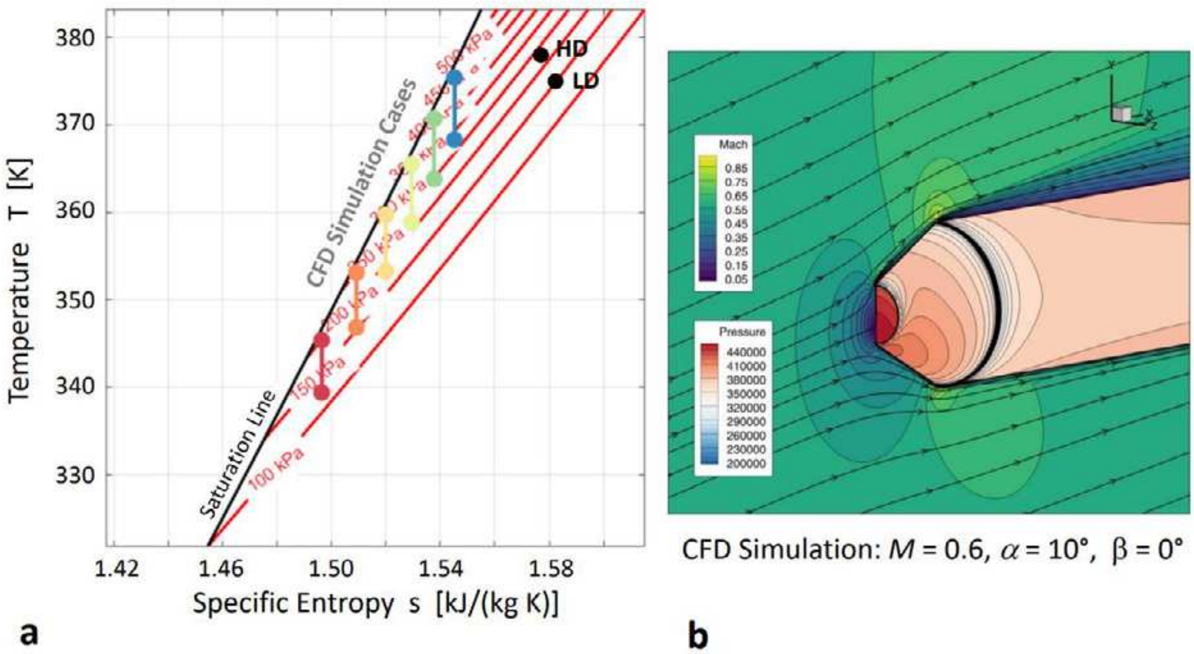

Figure 3: Calibration of multi-hole probes for Novec 649: **a** Simulated and experimentally investigated cases in the *T,s*-diagram; **b** simulated pressure and Mach number distribution for a case

In addition to the experimental calibration, the conical five-hole probe was the subject of a numerical calibration. Passmann et al. (2021) describe this approach in detail for air for the same probe design. In the present study, the flow of Novec 649 at several operation points, shown as colored symbols in Figure 3.a was simulated using the open-source CFD code SU2 (version 7.5.1). The k-ω-SST turbulence model and the PRSV cubic equation of state were employed for the CFD simulations. 47 An example of the computed Mach number and surface pressure distributions is shown in Figure 3.b. Considering the locations of the probe pressure holes, the calibration coefficients, see equations (1) and (2), were obtained using the computed surface pressure distribution. The exact geometrical modeling of the actual probe head is essential for the reliability of this numerical approach. Details about this item and the meshing can be found in Passmann et al. (2021).

4 RESULTS AND DISCUSSION

This section presents and briefly discusses the results of the numerical and experimental calibration of the multi-hole probes. Special attention is spent on potential deviations from the calibration coefficients and maps (i.e., calibration spaces) obtained for perfect gases in organic vapor flow applications.

4.1 Aligned Probes (Nulling Mode)

For aligned probes working in the so-called nulling mode, the lateral pressure values (hole 2 up to hole 5, Figure 1) are identical. Consequently, the yaw and the pitch coefficients vanish, and only the Mach number coefficient C_M and the total pressure coefficient C_{pt} remain as relevant probe quantities.

The Mach number coefficients C_M for aligned probes are plotted against the Mach number M in Figure 4. Although two different probe designs, shown in Figure 1, were used in the experiments and the CFD simulations, their general behavior was similar. As expected, the Mach number coefficient sensitivity vanished for $M \rightarrow 1$ (the gradient of C_M decreased for $M \rightarrow 1$). This is a fundamental problem of this kind of probe in the transonic flow regime (see Main et al. (1996) or Bachner et al. (2022)).

Interestingly, the numerically computed calibration curves for different stagnation conditions did not exactly collapse to a single curve in Figure 4 (right). In the case of a perfect gas, the Mach number coefficient would not depend on the stagnation state. In the case of Novec 649, a slight but systematic difference can be noticed for the two simulated cases shown in Figure 4 (right).

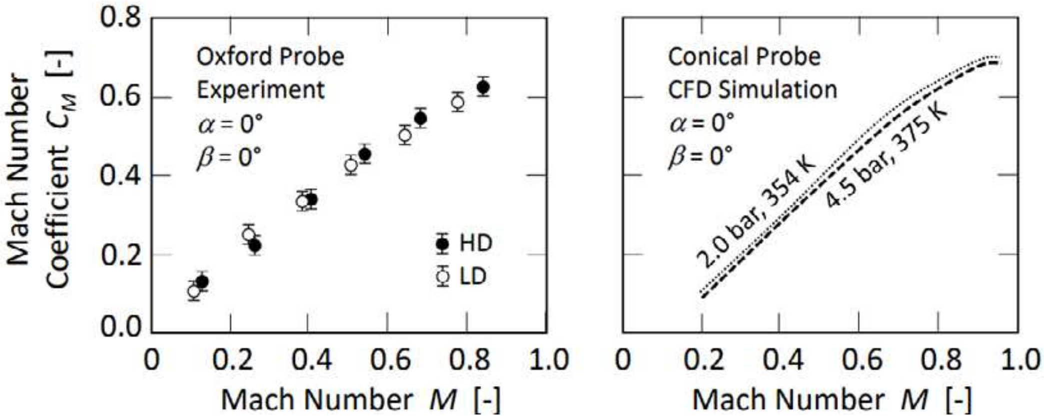

Figure 4: Mach number coefficient against Mach number for aligned probes in a flow of Novec 649

The total specific enthalpy values for the two CFD cases were h_t = 369.4 kJ/kg and 385.17 kJ/kg, respectively. Their compressibility values were Z = 0.9084 and 0.8189, respectively. For the experimental calibration data, Figure 4 (left), the nominal specific enthalpy was nearly identical for the HD and LD cases. Still, the actual values scattered for different Mach numbers due to the static temperature deviations of order 1 K, as explained in section 3. Hence, the impact of the initial stagnation state on the experimental result cannot be identified in Figure 4 (left). The error bars and the temperature scattering were too high for a definite conclusion. Hence, it was decided to conduct a detailed study at a constant running speed and nominal temperature levels to explore this NICFD issue (see the following subsection).

4.2 Three-Hole Probes (Non-Nulling Mode)

Considering non-zero yaw angles β and keeping the pitch angle α to zero, the probes become effectively three-hole probes. Then, the yaw angle, Mach number, and total pressure coefficients are the three relevant parameters for three-hole probes.

Regarding the impact of stagnation states on the calibration, a detailed study at constant compressor running speed and fixed Mach number was conducted for the two cases HD and LD, under their nominal thermodynamic conditions listed in Table 2. The outcome of the experimental and numerical calibrations at fixed Mach numbers are shown in Figure 5. Due to the different density levels, the actual Mach numbers were not identical for the HD and LD cases. Since the Mach number coefficient C_M depends on the Mach number M, the LD original data were corrected using the C_M,M-curve of Figure 4 (left). Figure 5 (left) shows the original and corrected data (in red) for the LD case at the same Mach number as for the HD case.

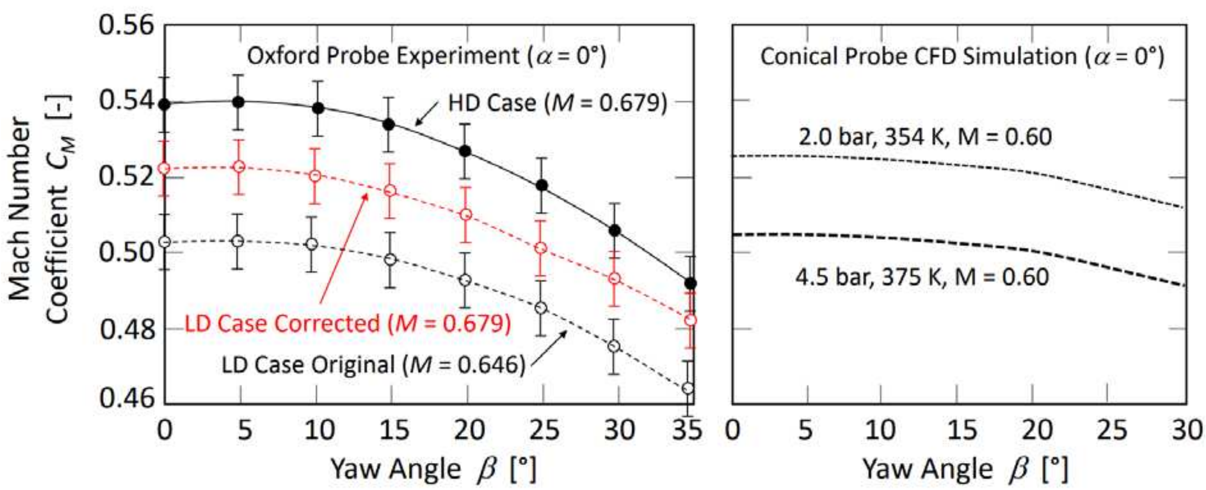

Figure 5: Mach number coefficient against yaw angle in a flow of Novec 649 at fixed Mach number

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An impact of the initial thermodynamic state on the Mach number coefficient C_M of about 5 % was observed for the corrected experimental data in Figure 5 (left). In the case of the original data, the difference would be even more considerable. However, since the Mach number dependency was significant, only the corrected LD data (red symbols in Figure 5, left) and the HD data (black symbols) should be compared. The same qualitative behavior and a similar deviation for the Mach number coefficient C_M were also observed in the CFD simulation cases, as shown in Figure 5 (right). In the CFD study, the Mach number was kept the same for the two simulated cases, and no correction was required.

The behavior of the yaw angle and total pressure coefficients is illustrated in Figure 6 for both probes. No systematic influence of the initial thermodynamic state was observed for these quantities. In the case of the CFD simulations, the two cases led to identical results, and hence the two CFD curves collapsed in Figure 6.

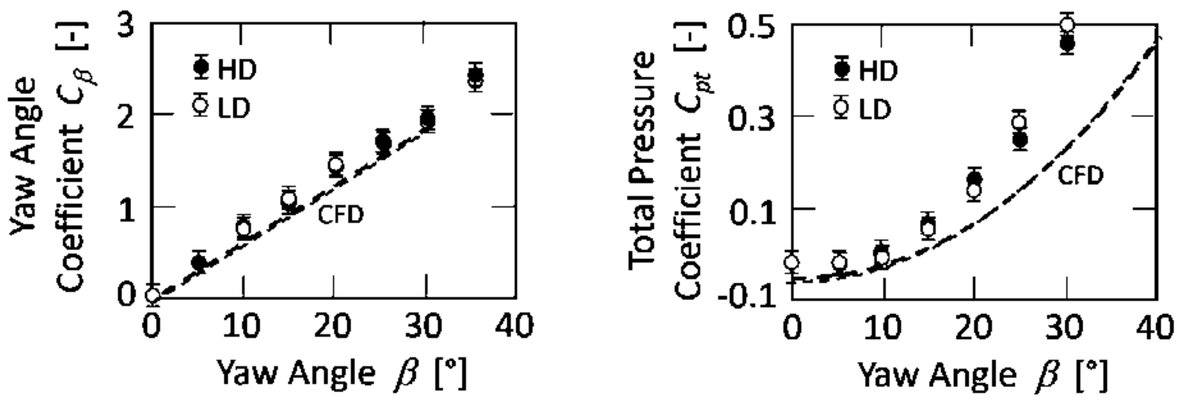

Figure 6: Yaw angle and total pressure coefficients against yaw angle at fixed Mach number

The CFD simulations covered the operation points shown in Figure 3; no significant differences were observed for the behavior of the yaw angle and total pressure coefficients as functions of the yaw angle β. The general behavior for the yaw angle and total pressure coefficients was similar for the pyramid and the conical probe. However, a systematic difference can be seen in the total pressure coefficient between the experimental data and the CFD simulations caused by the different probe heads. A good sensitivity was found for the yaw angle coefficient C_β, corresponding to the incompressible flow regime (Hall and Povey (2017)). The observed linear relation between C_β and β and the insensitivity against stagnation states are highly advantageous for flow angle measurement applications. The total pressure coefficient C_{pt} was insensitive against minor yaw angle variations for an aligned probe ($\beta \rightarrow 0$). This is a well-known feature of Pitot probes. For higher yaw angles, the total pressure coefficient C_{pt} exhibited a nonlinear functional dependency on β. Then, the actual probe head design becomes relevant, and a design-specific calibration is needed.

4.3 Practical Considerations for Five-Hole Probe Calibration and Use

The required efforts for a full experimental calibration of a five-hole probe for transonic flow measurements in an organic vapor are substantial, as illustrated by the following example: Following Main et al. (1996), data should be acquired at almost 10,000 individual combinations of pitch angle, yaw angle, and Mach number to calibrate a four-hole probe in the compressible flow of a perfect gas. This large number of points must be significantly increased to cover the impact of the thermodynamic state on the calibration. As a result, a four-dimensional calibration hyperspace must be covered. Furthermore, the calibration facility must be able to operate at the same thermodynamic conditions as planned for the later flow measurements. While it is not impossible to fulfill these requirements, it would be highly time-consuming and costly, severely restricting the use of multi-hole probes in compressible organic vapor flows. Based on these considerations, the following two strategies might offer a more sensible practical approach.

Firstly, the calibration efforts for a three-hole probe are within an acceptable range because the yaw angle and the total pressure coefficients are insensitive against initial states, see Figure 6. The impact of the initial states on the Mach number coefficient is of order 5 %, see Figure 5. It is recommended to use three-hole probes as a standard tool for flow angle determination and restrict the use of five-hole probes to particular studies. The five-hole probe should be used primarily in the nulling mode to limit the calibration efforts. But even then, the probes' size and required turning mechanism would create severe issues for experimental setups.

Secondly, the experimental calibration efforts can be significantly reduced by the numerical calibration method, as proposed by Passmann et al. (2021). Then, the experiments are only required for validation purposes, and a much lower number of data points is needed. This approach works particularly well for probes with a high degree of symmetry (i.e., cylindrical body shape or conical probe heads). Thus, this probe design is recommended for organic vapor flow measurements with five-hole probes in the non-nulling mode.

Artificial neuronal networks or machine learning methods for calibrating multi-hole probes might offer an attractive approach (see, for instance, Rediniotis and Vijayagopal (1999)). However, such an approach cannot avoid the fundamental non-ideal compressible flow dynamical issues and the need to gather a substantial amount of probe calibration data.

5 CONCLUSIONS

The following conclusions can be drawn from the experimental and numerical study of the behavior of multi-hole probes in organic vapor flows.

Dimensional analysis shows theoretically that the three-dimensional calibration space must be extended to a four-dimensional hyperspace for five-hole probes for organic vapor flows. In this case study, the initial thermodynamic state affected only the Mach number coefficient, not the angle or total pressure coefficients. This observation demonstrates that non-ideal compressible fluid dynamics must be accounted for in accurate ORC lab experiments and data reduction procedures. Since the Mach number coefficient C_M is involved in obtaining the static pressure p, this quantity needs special attention in the organic vapor flow field and turbine cascade loss measurements.

It was found that three-hole probes behaved well and offered good sensitivity regarding the flow angle determination. Since the calibration workload is at an acceptable level, the use of these devices can be recommended. Furthermore, three-hole probes can be manufactured and miniaturized easier than five-hole probes, supporting their practical use.

Due to their substantial calibration efforts, it is hard to recommend the five-hole probe as a standard tool for transonic flow measurements in organic vapors. The use of this device should be considered in the nulling mode or combination with reliable numerical calibration studies. But even then, the interaction of the relatively large probes with the flow and potential blockage issues might introduce substantial challenges.

NOMENCLATURE

C_α	pitch angle coefficient (see equation (1))	-
C_β	yaw angle coefficient (see equation (1))	-
C_M	Mach number coefficient (see equation (2))	-
C_{pt}	total pressure coefficient (see equation (1))	-
d	probe diameter	m
h	specific enthalpy	J/kg
M	Mach number	-
p	pressure	Pa
p^*_{dyn}	pseudo-dynamic pressure	Pa
Re	Reynolds number	-
s	specific entropy	J/(kg K)
T	temperature	K
Tu	turbulence intensity	-

U	velocity	m/s
X	thermodynamic similarity variable	-
Z	compressibility factor	-

Greek symbols

α	pitch angle (see Figure 1)	°
β	yaw angle (see Figure 1)	°
γ	isentropic exponent	-
Γ	fundamental derivative of gas dynamics	-
μ	dynamic viscosity	Pa s
ρ	density	kg/m3

Subscript

avg	average
t	total or stagnation state
1, 2, …	hole numbering (see Figure 1)

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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