# A USER-FRIENDLY PITOT PROBE DATA REDUCTION EXCEL-REFPROP-ROUTINE FOR NON-IDEAL GAS FLOW APPLICATIONS

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## ABSTRACT

This contribution presents a user-friendly data reduction routine for Pitot probes based on widely available software with a fluid properties interface. The data reduction process rests on the general balance equations and the fluid database and calculation program REFPROP by NIST. In the corresponding calculation sheet, the user can easily select the fluid and manually or automatically insert the probe data and stagnation conditions of the measurement. A robust algorithm directly calculates the freestream Mach number and other flow and thermodynamic quantities. The new Pitot probe data reduction routine's accuracy is assessed through several test cases, including the subsonic and supersonic flow of dry air, Novec 649, and siloxane MM in the dilute and dense gas regime. For compressible non-ideal gas flows, it is found the classical Rayleigh-Pitot equation is systematically in error even in the dilute gas regime where relative deviations of more than 10 % were noticed. In the dense gas regime, the Rayleigh-Pitot equation fails dramatically in calculating the freestream Mach number, and errors larger than 60 % were observed.

## 1 INTRODUCTION

For obtaining and quantifying losses in turbomachinery, total pressure data are required (Dixon and Hall (2010)). The classical device for obtaining total pressure data is the Pitot probe. This device is also the natural starting point for more complex pneumatic probes, like the five-hole probe. In order to improve the efficiency of turbines for organic Rankine cycle (ORC) applications, it is obvious to conduct experiments and cascade testing in suitable organic vapor wind tunnels utilizing Pitot probes (Spinelli et al. (2013), Reinker et al. (2015), Head et al. (2016)).
The theory of Pitot probes and the corresponding data reduction process, e. g., the famous Rayleigh-Pitot equation, are well treated in numerous textbooks, e.g., John and Keith (2006) or Liepmann and Roshko (2001), in the case of a perfect gas. For that, analytical expressions can be derived, making the use of Pitot probe data for flow investigations relatively easy. However, much less is known about the data reduction process in compressible non-ideal gas flows. Especially in the so-called dense gas regime, the Rayleigh-Pitot equation's use becomes notoriously questionable. A data reduction method is needed to cover the non-ideal gas behavior for isentropic flow and shock relations.
In the past, numerical methods for calculating non-ideal gas effects have been proposed and successfully employed in Pitot measurements (Reinker et al. (2020)). However, at least in our laboratory team, students and research assistants had a strong interest in utilizing a user-friendly routine running on EXCEL in combination with REFROP by NIST (N.N. (2021)). Such a solution and its underlying sub-routines are presented in the following after a brief review of Pitot probe measurements' fundamentals. Proposing a data reduction method resting on a commercial software like the MS office program EXCEL opens, in principle, the present contribution to criticism. Regarding a wide range of potentials users, a code in Python connected to CoolProp (that would be made available in GitHub or as a web interface where the users can add inputs and calculate the results) would be ideal. However, from the author's experience, practically every laboratory or research and development department has access to

EXCEL and REFPROP today, and so the limitations due to the commercial constraints might be weak in practice. However, it would be certainly worthwhile to develop an open-source code for Pitot probe data reduction for the scientific community. The interested reader can find in the following the numerical scheme and might find it attractive to create its own code based.

## 2 PITOT PROBE FUNDAMENTALS

The stagnation (or total) pressure is measured by an instrument that brings the flow isentropically to rest. Such a device is usually called a Pitot probe, and its history can be traced back to the year 1732. Several probe geometries and combinations with static pressure taps are now available for obtaining Mach number and velocities in compressible flows, as discussed by John and Keith (2006). In the case of turbomachinery applications, cylinder probes are also common, see Wyler (1975). Despite the numerous sizes and designs of Pitot probes, the fundamentals are still the same, see Fig. 1. The isentropic flow relations are always fundamental for the data reduction process using Pitot probe pressure (the total pressure denoted by subscript o in the following) and the static pressure.

### 2.1 Perfect Gas Flows

In subsonic perfect gas flow, see Fig. 1.a, the freestream flow Mach number $Ma_1$ can be directly determined from the measured total pressure $p_{o1}$ (Pitot probe pressure) and (known) free static pressure $p_1$ using the well-known isentropic flow relation

$$Ma_1^2 = \frac{2}{\gamma-1}\left(\left(\frac{p_{o1}}{p_1}\right)^{(\gamma-1)/\gamma} - 1\right). \tag{1}$$

In the case of supersonic perfect gas flow, see Fig. 1.b, the Pitot probe acts as a blunt-nosed body, and there will be a detached bow shock in front of the probe. Then, it is necessary to distinguish between a station upstream of the shock (denoted by subscript 1) and a station downstream of the shock (denoted by subscript 2). In the data reduction process, it is then necessary to include also the normal shock relations, and the well-known Rayleigh-Pitot equation

$$\frac{p_{o2}}{p_1} = \frac{\gamma+1}{2} Ma_1^2 \left(\frac{(\gamma+1)^2 Ma_1^2}{4\gamma Ma_1^2 - 2(\gamma-1)}\right)^{1/(\gamma-1)}. \tag{2}$$

results in the case of a perfect gas with an isentropic exponent $\gamma$. For a given perfect gas, the inflow Mach number $Ma_1$ can be obtained using only the measured Pitot probe pressure $p_{o2}$ and the free static pressure $p_1$. In supersonic flows, Eq. (2) is typically solved iteratively for $Ma_1$. In subsonic flow, $p_{o2} = p_{o1}$ holds, and the Mach number is determined by Eq. (1).

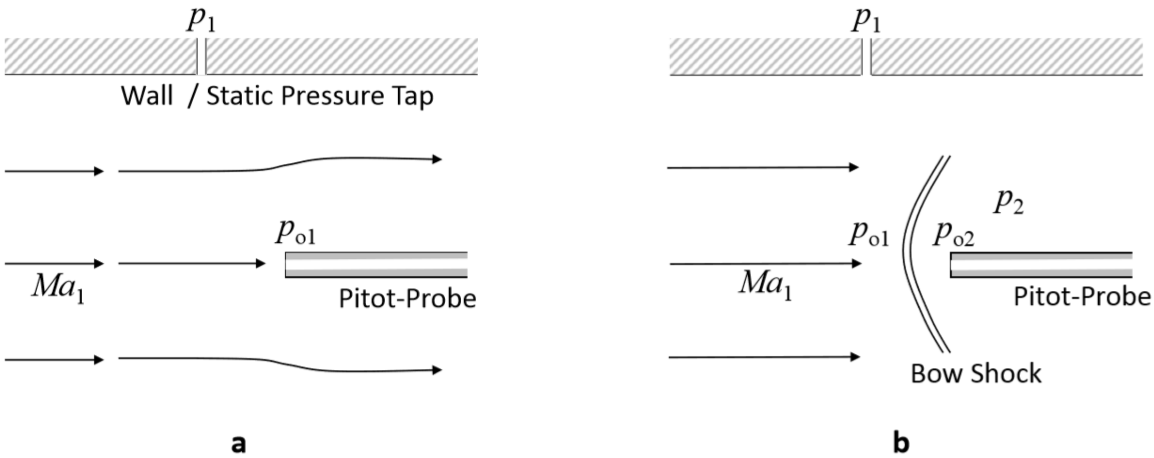


**Figure 1:** Pitot probe in subsonic flow (**a**) and in supersonic flow with a bow shock (**b**)

### 2.2 Non-Ideal Gas Flows

In non-ideal gas flows, the qualitative thermodynamic behavior illustrated in Fig. 2 remains somewhat similar.

In subsonic flows, Fig. 2.a, the Mach number $Ma_1$ can be directly calculated by an isentropic flow relation $Ma_1 = f_s(p_1, p_{o1}, h_{o1})$ assuming $s = s_1 =$ constant. In the case of non-ideal gas flows, the isentropic flow relations $f_s$ are not universal; they depend in general on the stagnation state $\{h_{o1}, p_{o1}\}$. It is usual to calculate the stagnation enthalpy $h_{o1}$ using the measured total temperature $T_{o1}$ and total pressure $p_{o1}$. In wind tunnel experiments, it is often common to identify $h_{o1}$ with the settling chamber value, i.e., with $h_0 = h(T_0, p_0)$ where $T_0$ and $p_0$ are the settling chamber temperatures and pressures, respectively.

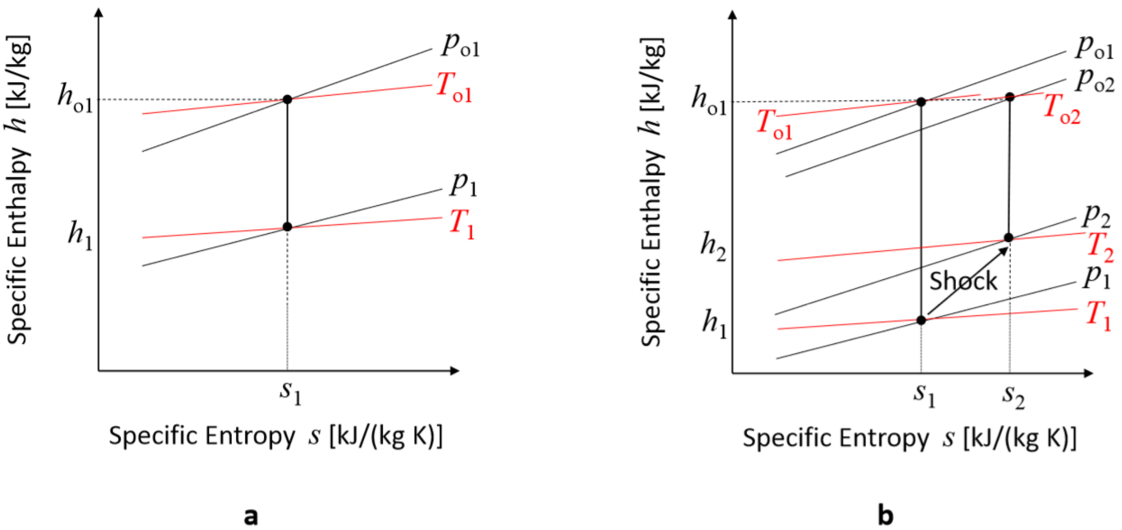


**Figure 2:** Thermodynamics of a Pitot probe in subsonic flow (**a**) and in supersonic flow (**b**)

In supersonic flows, Fig. 2.b, the shock between 1 and 2 requires more effort in calculating the inflow Mach number $Ma_1$. Typically, the stagnation enthalpy $h_{o1} = h_{o2}$ is already known (this value is identified with the settling chamber value $h_0$ in a wind tunnel experiment). Furthermore, the Pitot probe provides the downstream total pressure $p_{o2}$, and additional static wall pressure measurements provide the upstream static pressure $p_1$, see also Fig. 1.b. In this case, the unknown inflow Mach number $Ma_1$ (and other flow variables) can be calculated by solving the general balance equations for mass, energy, and impulse

$$\rho_1 c_1 = \rho_2 c_2, \tag{3a}$$

$$h_1 + \frac{1}{2}c_1^2 = h_2 + \frac{1}{2}c_2^2 = h_0, \tag{3b}$$

$$p_1 + \rho_1 c_1^2 = p_2 + \rho_2 c_2^2. \tag{3c}$$

Due to the quadratic velocity terms in Eq. (3), two solutions can result, but only the solution with $s_2 > s_1$ is physically correct since the second law of thermodynamics has to be obeyed for the shock.

In the case of a perfect gas with constant properties, the above set of equations can be solved analytically; then, in the supersonic case, the well-known Rayleigh-Pitot equation (2) results. A different mathematical approach for solving the set of equations (3) has to be employed for fluids not obeying the perfect gas laws.

## 3 DATA REDUCTION METHOD

It is possible to employ a quasi-analytical formalism proposed by Passmann et al. (2017) to solve the above set of equations. In that case, it is necessary to solve a cubic equation for the specific volume v

$= 1/\rho$. Although such an approach might be elegant in terms of mathematics since the establishment of the famous Cardano formulas, it is not very attractive for practical applications. Hence, a different approach based on an appropriate fluid database and equation of states were employed in the following.

### 3.1 Program Structure and Flow Chart

The general structure of the data reduction routine is shown in Fig. 3. The input data are (after the fluid selection) the Pitot probe pressure (in the following generally denoted by $p_{o2}$ even in the subsonic flow case), the free static pressure $p_1$, and the stagnation enthalpy $h_0$ that is usually calculated as a function of the settling chamber pressure $p_0$ and temperature $T_0$ in a typical wind tunnel experiment. All thermodynamic properties are calculated by means of REFPROP by NIST. A feature of REFPROP permits the utilization of REFPROP results within EXCEL. In addition to the primary input data, the user might choose specific step sizes for the algorithm based on the solution control parameters' output. Within the routine, a standard set of step sizes as default values is already provided, but the user might try to improve the results' accuracy by choosing smaller step sizes. The primary output quantity is the inflow or freestream Mach number $Ma_1$, but several other flow and thermodynamically output data like pressure, temperature, and sound speed are provided. The main flow chart of the EXCEL-based routine is shown in Fig. 4.

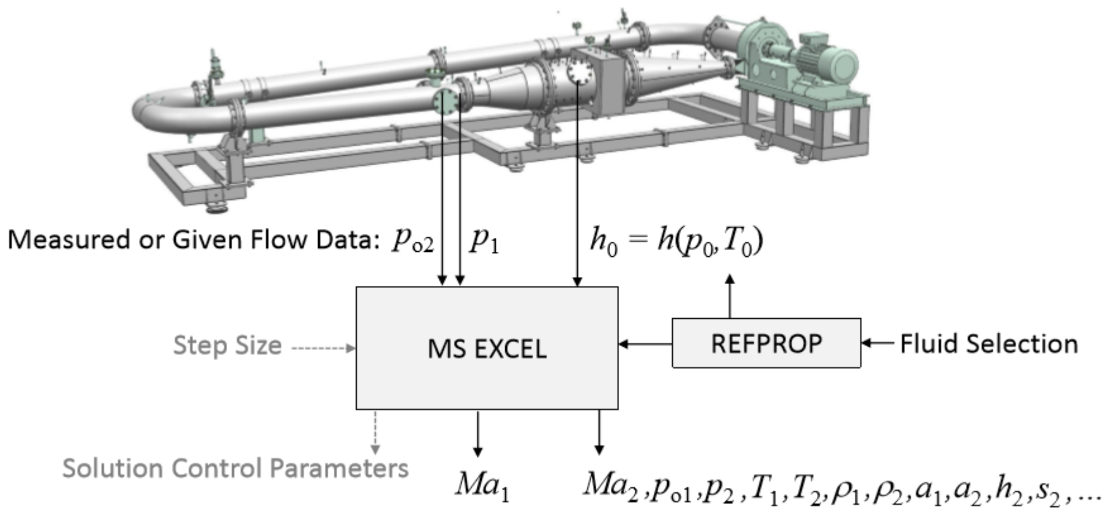


**Figure 3:** General structure of the EXCEL-based data reduction routine for Pitot probes

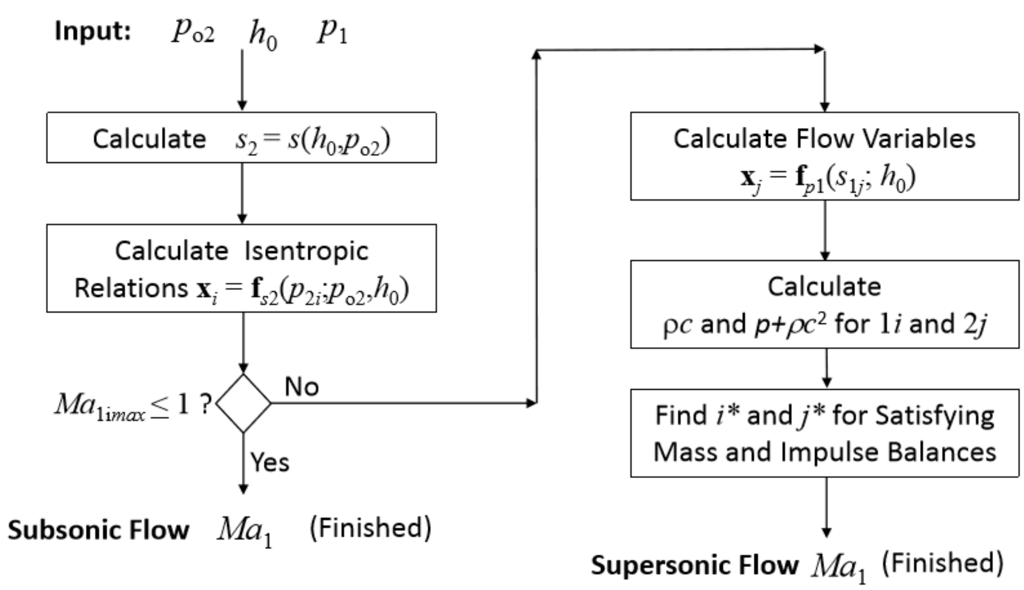


**Figure 4:** Main flow chart of the data reduction process

In the first step, the specific entropy $s_2$ is calculated using the stagnation enthalpy $h_0$ and the Pitot pressure $p_{o2}$. Using $s_2$, the isentropic flow relations $\mathbf{x} = \mathbf{f}_{s2}$ for the flow and thermodynamically quantities at the Pitot probe station 2 are calculated for a fair number of values $p_{2i}$. In Fig. 4, a vector notation $\mathbf{x} = (h_2, T_2, \rho_2, c_2, a_2, Ma_2, \ldots)$ is used to characterize the thermodynamic state. The static pressure $p_{2i}$ starts at $p_{2,i=1} = p_{o2}$ and it stops at $i = i_{max}$ corresponding to $p_{2imax} = p_1$. The total number of $i_{max}$ depends on the chosen step size for calculating an isentropic table for station 2, which should be fine enough for achieving the desired accuracy (see also later section).
If $Ma_{2imax} = \mathrm{f}_{s2}(p_{o2}, p_1; h_0) \leq 1$, the subsonic flow results have already been calculated on the basis of the isentropic relation (analog to Eq. (1) in the case of a perfect gas flow), and the routine is finished.
If $Ma_{2imax} > 1$, the routine has to go through the supersonic path. In the supersonic flow case, a second table for the (unknown) station 1 upstream of the shock has to be calculated. In this case, the static pressure $p_1$ and total enthalpy $h_{o1} = h_0$ are assumed to be constant, and flow and thermodynamically variables $\mathbf{x}_j$ are computed for different values of specific entropy $s_{1j}$. Here, $j = 1$ corresponds always to $s_{1,i=1} = s_2$, and $s_{1,jmax}$ corresponds to $s_0$ (i.e., the entropy $s_0$ of the settling chamber represents the lower limit due to the second law of thermodynamics).
Using the calculated states $\mathbf{x}_i$ and $\mathbf{x}_j$ at station 1 and station 2, the mass flow and impulse expressions $\rho c$ and $p + \rho c^2$ are computed (see Eq. (3)) for any $i$ and $j$. Based on these expressions, the set $(i^*, j^*)$ is identified, which satisfied simultaneously the mass balance and the impulse balance (the energy balance is already satisfied since $h_0 = h_{o1} = h_{o2}$ is assumed throughout). For identifying $(i^*, j^*)$, the expression $p + \rho c^2$ is plotted against $\rho c$ for $i$ and $j$, respectively. The intersection of the two lines provides the desired solution $(i^*, j^*)$ and hence the desired freestream Mach number $Ma_1$ and the other quantities. Since the shock relations have mathematically two solutions, only the solution characterized by $s_1 \leq s_2$ is selected.

### 3.2 Solution Control Parameters and Numerics

Although the present data reduction rests entirely on the actual (real gas) fluid behavior as covered by REFPROP, it is interesting to compare the computed results with the predictions by the simple perfect gas expression (see Eq. (1) and Eq. (2)). Hence, as an additional feature, the isentropic exponent $\gamma = c_p/c_v$ is calculated by REFPROP using $h_0$ and $p_{o2}$ and then inserted into the perfect gas expressions (i.e., assuming the perfect gas expressions). The outcome of this perfect gas calculation method is compared with the results of the general data reduction. In the case of a perfect gas, both ways should provide essentially the same. In the case of significant non-ideal gas behavior, substantial deviations can occur between the two methods. However, if the difference between the two methods is too extreme, the user might also consider a check of the actual calculation and the input data.
The data reduction routine provides default values for the steps $\Delta p_2 = p_{2i} - p_{2,i+1}$ and $\Delta s_1 = s_{1j} - s_{1,j+1}$ but the user is free for changing these numerical parameters. In the case of large step sizes, the tables at station 1 and 2 might be too coarse, and the flow quantities like $Ma_1$ might be provided with large uncertainty. In addition to the obvious strategy to reduce the step size (which increases the computational running time), it is possible to use polynomial fitting functions for $p + \rho c^2$ as a function of $\rho c$ (for $i$ and $j$ as marching indices) and to compute the intersection $(i^*, j^*)$ through these fitting functions. This interpolation algorithm works well since $p + \rho c^2$ as a function of $\rho c$ are typically monotonically for a wide class of fluids and input data. The intersection is also shown graphically in an auxiliary EXCEL sheet, including all tables and station values.

### 3.3 Using the Routine

The routine is implemented as EXCEL document. After selecting the fluid on the main sheet, the user can manually type the required input data or provide a scan number from a recorded lab software file (if available). Only the scan number is needed in the latter case, and the system provides the pressure and enthalpy values. In the manual input procedure, the user has to specify the two pressure values $p_1$ and $p_{o2}$. Still, the user can choose between two options: direct input of $h_0$ or providing settling chamber pressure and temperature values $p_0$ and $T_0$, respectively.
After completing the input, the data reduction starts directly and provides the results at the main calculation sheet. Based on the computed Mach number $Ma_1$, the output distinguishes between the subsonic and supersonic flow. In the supersonic flow case, all values upstream and downstream of the

shock are provided. A comparison with the perfect gas data reduction methods is provided, too. Here, absolute values for the Mach number and the relative errors are listed. In addition to the main calculation sheet, auxiliary sheets are created automatically. In addition to the tables of thermodynamic expressions, the solution of the coupled mass and impulse balance equations are graphically shown in secondary sheets. The intersection is explicitly reported in the diagram, and the values closest to that are marked in green color in the tables. If necessary, the user can change the step size manually and repeat the computation.

# 4 TEST AND APPLICATION

In the first set of test runs, the impact of the step size on the calculated Mach number was investigated. After determining the required step size, the data reduction routine was tested through three different fluids covering perfect gas up to dense gas regime applications.

## 4.1 Impact of Step Size

It was found that the impact of step size on the calculated Mach number $Ma_1$ and other flow parameters was modest for typical applications. As a general rule, the pressure step size should be of order $\Delta p_2/p_{o2} \approx 1$ %, and the entropy step size should be of order $\Delta s_1/s_2 \approx 0.05$ %. With such step sizes, the Mach numbers and other flow parameters can be computed with acceptable accuracy. In principle, it is possible to achieve an exact solution through sufficiently small step sizes.

In Table 1, two representative examples are listed. The exact results are achieved if the residuals in the balance equations (3) are zero. The deviations between the exact results and the outcome of the computations with default step sizes were of order 0.6 up to 1.2 %. For practical applications, it is recommended to assess the impact of step size on actual data reduction by performing some preliminary test runs with characteristic input data for the experiments under consideration.

**Table 1:** Effect of size step on calculated Mach number

| **Fluid / $h_0$** | $p_{o2}$ | $p_1$ | $\Delta s$ | $Ma_1$ |
|---|---|---|---|---|
| NOVEC 649 / 399.36 kJ/kg | 4.5 bar | 1.5 bar | 0.0008 kJ/(kg K) | 1.590 |
| NOVEC 649 / 399.36 kJ/kg | 4.5 bar | 1.5 bar | 0.0004 kJ/(kg K) | 1.581 (exact) |
| MM / 407.98 kJ/kg | 38 bar | 10 bar | 0.0030 kJ/(kg K) | 2.002 |
| MM / 407.98 kJ/kg | 38 bar | 10 bar | 0.0027 kJ/(kg K) | 2.027 (exact) |

## 4.2 Application Cases

The practical value of the present data reduction routine can be assessed by performing some representative test case calculations. In the following, three fluids are considered, namely dry air (representing a perfect gas), NOVEC 649 at moderate pressure and temperature levels (representing a non-ideal gas with only minor deviations from a perfect gas), and MM ($C_6H_{18}OSi_2$ – hexamethyldisiloxane). For the two organic vapors, two different stagnation conditions were considered, which are illustrated by their location in the temperature-entropy diagrams, see Fig. 5.

### 4.2.1 Dry Air

In the case of dry air at pressure levels of about 2 up to 10 bar and temperature levels of about 100°C, the deviations between the classical Rayleigh-Pitot equation and the EXCEL-based data reduction routine using the REFPROP data for dry air remained relatively small (of order 0.1 % over the entire practical Mach number range). This slight deviation level indicates that the classical Rayleigh-Pitot equation is reliable for compressible air flows and that there is no real need to consider real-gas effects for air flows at this pressure and temperature level for data reduction.

### 4.2.2 NOVEC 649

In a second test run, the deviations between the Rayleigh-Pitot equation and the data reduction using REFPROP data for NOVEC 649 were assessed.

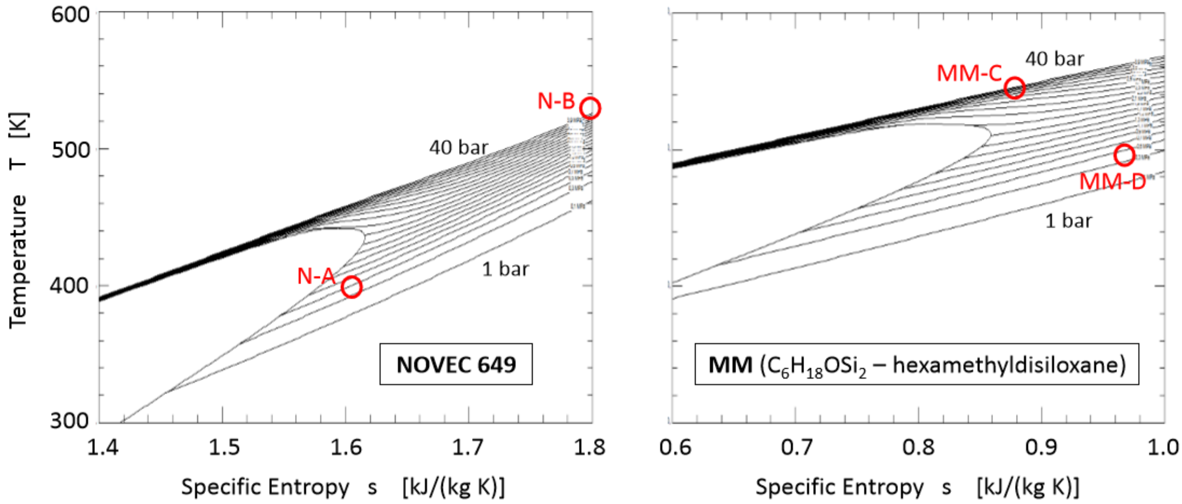


**Figure 5:** Stagnation conditions for the test cases in the *T,s*-diagrams for Novec 649 and MM

The considered pressure and temperature levels were in parts roughly oriented to typical operating conditions of the test facility CLOWT at Muenster University of Applied Sciences (Reinker et al. (2020)). However, in addition to the moderate pressure test case (called N-A, see Fig. 5), a further set (called N-B) at higher pressure was considered.

In Table 2, the NOVEC 649 test cases and the outcome regarding the Mach number errors are listed. For the two sets, the stagnation enthalpy $h_0$ and the static pressure $p_1$ were assumed to be fixed. Values for the freestream Mach number $Ma_1$ and the Mach number $Ma_2$ after the shock in front of the Pitot probe were calculated for a range of Pitot pressure values $p_{o2}$ using the new data routine and Rayleigh-Pitot formula. The relative deviation between these values was considered as an error. The maximum errors are listed in Table 2.

In the case of moderate pressure level, the perfect gas equations introduced significant Mach number errors of order 5 % in the subsonic, transonic and supersonic flow regimes. Such an error level is substantially larger than the usual experimental uncertainty levels. This error was even higher in the second set of higher pressure levels and exceeded 10 %. This means that the data reduction method has to consider the non-ideal gas behavior, although NOVEC 649 behaves in this regime still similar to a perfect gas. Even in the dilute gas regime, the classical Rayleigh-Pitot formula might be substantially in error, and relative deviations between the classical Rayleigh-Pitot formula and the proposed method of more than 10 % can occur.

**Table 2:** Considered Novec 649 test cases

| Test Case | Stagnation enthalpy $h_0$ | Static pressure $p_1$ | Pitot pressure range $p_{o2}$ | Maximum error $\Delta Ma_1/Ma_1$ | Maximum error $\Delta Ma_2/Ma_2$ |
|---|---|---|---|---|---|
| N-A | 399.4 kJ/kg | 2.0 bar | 2.2 up to 7 bar | 4.9 % | 4.7 % |
| N-B | 543.5 kJ/kg | 10 bar | 12 up to 38 bar | 8.2 % | 10.9 % |

4.2.3 MM in non-ideal and quasi-ideal flow conditions

Finally, some test runs with MM were performed to assess the reliability of the data reduction in the non-ideal flow regime, see Fig. 5. The test case called MM-C corresponded to the flow in the dense gas regime, whereas the case MM-D was located farther away from the critical point where a quasi-ideal gas flow can be expected. In Table 3, the considered MM test cases and the outcome regarding the Mach number errors are listed. In Fig. 6, the relative errors regarding freestream Mach number $Ma_1$ are plotted for the MM test cases. The relative errors are substantial if the Rayleigh-Pitot equation would be used in the dense gas regime, test case MM-C.

**Table 3:** Considered MM test cases

| Test Case | Stagnation enthalpy $h_0$ | Static pressure $p_1$ | Pitot pressure range $p_{o2}$ | Maximum error $\Delta Ma_1/Ma_1$ | Maximum error $\Delta Ma_2/Ma_2$ |
|---|---|---|---|---|---|
| MM-C | 408.0 kJ/kg | 10 bar | 12 up to 38 bar | 69 % | 66 % |
| MM-D | 399.4 kJ/kg | 2.0 bar | 2.2 up to 7 bar | 3.4 % | 2.9 % |

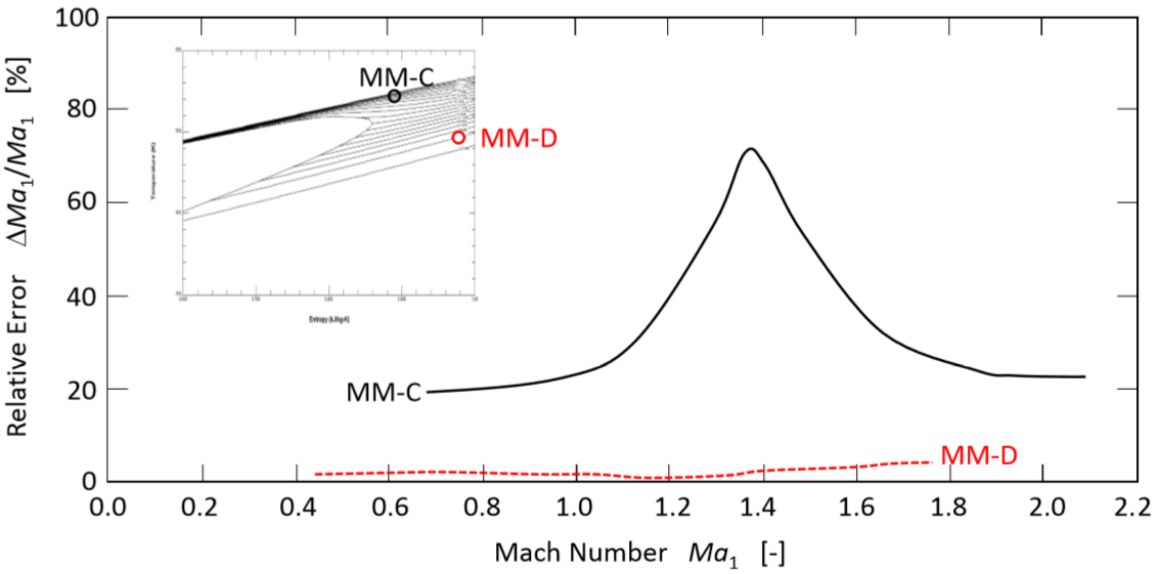


**Figure 6:** Relative errors regarding freestream Mach number determination for the MM test cases

Even in the high subsonic flow, the error would be higher than 20 % for MM in the dense gas regime. Maximum errors of 69 % were noticed for supersonic flow. On the other hand, the error in the dilute gas regime, test case MM-D, remained relatively small.
It is certainly interesting to investigate in detail the main reasons for the poor performance of the classical Rayleigh-Pitot formula in dense gas applications. One reason could be the strong variation of the isentropic exponent, which makes it hard to define an appropriate, effective value in that regime.

### 4.3 Comparison with the Quasi-Analytical Method

Although it is possible to utilize a quasi-analytical formalism proposed by Passmann et al. (2017) for Pitot probe data reduction, numerical efforts are required for solving the cubic equation in practical applications for that method, too. Regarding the test case discussed in Passmann et al. (2017), no relevant numerical deviations were found (the numerical deviations were within the numerical error tolerance level of order 0.1 % for the computations, including rounding errors). Furthermore, no difference regarding the running time on a standard PC was observed.

## 5 SUMMARY

A user-friendly Pitot probe data reduction routine based on widely available office software was developed. The data reduction process employed the fluid database REFPROP by NIST. A rather robust algorithm directly calculated the Mach number and other flow and thermodynamic quantities within EXCEL. The accuracy of the new Pitot probe data reduction routine was assessed through several test cases, including the subsonic and supersonic flow of dry air, Novec 649, and siloxane MM in the dilute and dense gas regime. For compressible non-ideal gas flows, it was found that substantial errors can occur if the classical Rayleigh-Pitot would be used. Especially in the dense gas regime, the Rayleigh-Pitot formula fails dramatically in calculating the freestream Mach number.

## NOMENCLATURE

| | | | | | |
|---|---|---|---|---|---|
| $a$ | sound speed | (m/s) | $p$ | pressure | (Pa) |
| $c$ | velocity | (m/s) | $s$ | specific entropy | (J/(kg K)) |
| $f_s$ | isentropic relation | (–) | $T$ | temperature | (K) |
| $h$ | specific enthalpy | (J/kg) | $\mathbf{x}$ | thermodynamic state vector | |
| $Ma$ | Mach number | (–) | | | |

**Greek Symbols**

| | | | | | |
|---|---|---|---|---|---|
| $\gamma$ | isentropic exponent | (–) | $\rho$ | density | (kg/m$^3$) |

**Subscripts**

| | | | |
|---|---|---|---|
| $i$ | index variable (Pitot probe) | 0 | stagnation condition |
| $j$ | index variable (freestream) | 1 | upstream of shock (freestream) |
| o | total | 2 | downstream of shock (Pitot) |

**Supercript**

| | |
|---|---|
| * | solution (for index variables $i$ and $j$) |

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