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Journal of Physics: Conference Series, Vol. 821, N. 1, 2017, 012005 (10 pages)

doi:10.1088/1742-6596/821/1/012005

The final publication is available at <http://dx.doi.org/10.1088/1742-6596/821/1/012005>

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Non-Ideal Compressible-Fluid Dynamics of Fast-Response Pressure Probes for Unsteady Flow Measurements in Turbomachinery

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Abstract. The dynamic response of pressure probes for unsteady flow measurements in turbomachinery is investigated numerically for fluids operating in non-ideal thermodynamic conditions, which are relevant for e.g. Organic Rankine Cycles (ORC) and super-critical CO₂ applications. The step response of a fast-response pressure probe is investigated numerically in order to assess the expected time response when operating in the non-ideal fluid regime. Numerical simulations are carried out exploiting the Non-Ideal Compressible Fluid-Dynamics (NICFD) solver embedded in the open-source fluid dynamics code SU2. The computational framework is assessed against available experimental data for air in dilute conditions. Then, polytropic ideal gas (PIG), i.e. constant specific heats, and Peng-Robinson Stryjek-Vera (PRSV) models are applied to simulate the flow field within the probe operating with siloxane fluid octamethyltrisiloxane (MDM). The step responses are found to depend mainly on the speed of sound of the working fluid, indicating that molecular complexity plays a major role in determining the promptness of the measurement devices. According to the PRSV model, non-ideal effects can increase the step response time with respect to the acoustic theory predictions. The fundamental derivative of gas-dynamic is confirmed to be the driving parameter for evaluating non-ideal thermodynamic effects related to the dynamic calibration of fast-response aerodynamic pressure probes.

1. Introduction

Time resolved measurements of fluid properties in highly unsteady flows are nowadays fundamental for turbomachinery design and development. Indeed, several phenomena related to the turbine stator-rotor interactions, such as wake transport and rectification, wake-induced boundary layer transition, vortex migrations and boundary layer shock-wave interaction significantly affect the overall stage efficiency and have other consequences, including noise and thermal stresses [1]. Among the most relevant instrumentations currently employed in experiments, fast-response aerodynamic pressure probes stand out for their capability to measure both flow velocity and pressure field with a dynamic response of several tens of kHz, thus allowing to resolve the unsteadiness downstream of turbomachinery rotors (see for example [2, 3, 4, 5, 6, 7]). These devices went through an intensive development during the last decades



[8, 9, 10] and their designs considerably differ from conventional pneumatic probes used for measuring steady cascade performances.

The development of fast-response aerodynamic pressure probes has mostly profited from the installation of micro piezoresistive sensors and the finalization of robust flow reconstruction techniques to resolve the flow field by means of multiple measurements taken at different times, allowing higher frequency responses and lower blockage effects due to installation of single hole pressure probes that reduce the probe heads size [11, 10]. Piezoresistive transducer can be flash-mounted [9] or encapsulated within the sensor to enhance the probe strength [12, 8]. The latter configuration implies the overall dynamics to be influenced by the resulting line-cavity system, connecting the external domain to the piezoresistive transducer. Its geometrical configuration is of major importance to determine the dynamic properties of fast-response aerodynamic pressure probes, which can vary considerably with different internal designs [10]. The probe response also depends on the thermo-physical properties of the fluid and accurate models were proposed by relying on the so-called ideal, dilute gas assumption, which delivers acceptable predictions in most working conditions [10].

Molecularly complex fluids operating in non-ideal conditions are employed in turbomachinery applications in the frame of Organic Rankine Cycle (ORC) [13, 14]. In these conditions, the fluid behaviours can significantly depart from ideal gas model predictions [15, 16], typically in the close proximity of the saturation curve [17, 18]. To extend the applicability of measurement techniques devised for dilute gas flow to non-ideal compressible-fluid flows within ORC turbines, a shortcoming in the available analytical and experimental data calls for a careful investigation of the physics of measurement devices in the limit of non-ideal flows. Such an extension procedure is not straightforward in the non-ideal, compressible-fluid regime, due to e.g. the non-ideal dependence of the speed of sound on the density along isentropic transformation, high compressibility and possibly phase transition. In these conditions, the fluid thermodynamics is to be computed via complex, namely non-ideal, Equations of State (EoS).

The aim of this work is to provide a dynamic characterization of a selected fast-response pressure probe geometry operating in the non-ideal fluid regime. To this end, the open-source software suite SU2 [19], which has been recently extended to deal with Non-Ideal Compressible-Fluid dynamics (NICFD) [20] is used to carry out step response simulations, where a finite pressure perturbation, namely a shock wave, is applied at the inlet of the line-cavity system and the resulting pressure inside the cavity is evaluated to produce a time signal. This configuration reproduces the experimental setup implemented at Politecnico di Milano for the characterization of fast-response pressure probes in dilute air [10, 21]. The selected non-ideal fluid is siloxane MDM (octamethyltrisiloxane), which is currently used in relatively high enthalpy ORC systems [22]. The NICFD solver embedded in SU2 is based on the Peng-Robinson Stryjek-Vera (PRSV) thermodynamic model, which provides a good trade-off between accuracy, computational cost and uncertainties, because it relies on a limited number of parameters [23]. Dynamic characterizations is carried out by using both the dilute ideal gas (PIG) and the PRSV models.

The simulated operating conditions are based on two applications that involve siloxane fluid MDM. The first operating condition corresponds to test conditions to be observed within the Test-Rig for Organic Vapors (TROVA) at Politecnico di Milano [24, 25, 26]. The experiment is aimed at observing for the first time non-ideal nozzle flows relevant to ORC applications. The second test condition is taken from an existing axial organic Rankine stator nozzle, first presented in [16] and further studied recently in [27]. Operating conditions of the two cases are gathered in table 1.

This work is organized as follows: section 2 presents a description of the selected fast-response aerodynamic pressure probe, the dynamic characterization methods and the assessment of the numerical method against available experimental data for air in dilute; section 3 presents the

Table 1. Operating conditions for MDM. The corresponding speed of sound values are computed both using the PIG and the PRSV models. The subscript 0 indicates the operating conditions.

Operating Condition	P [bar]	T [C]	c_0^{PIG} [m/s]	c_0^{PRSV} [m/s]
A (TROVA)	25	310.3	144.5	117.8
B (Stator nozzle [28])	8	270.5	139.5	96.7

thermodynamic model and discusses possibly observable non-ideal effects; section 4 reports the results of the dynamic characterization carried out with MDM along with a comparison between PIG and PRSV models previsions; finally section 5 contains the conclusion.

2. Numerical modelling of fast-response pressure probes

Single-hole pressure probes are applied for 2D or 3D dynamic measurements as virtual three-hole or virtual five-hole probes. Indeed, the yaw angle cannot be resolved instantaneously, though the flow unsteadiness can be resolved through ensemble-averaging methods, which allow the field reconstruction. Reference [10] presents the design and the analysis of fast-response aerodynamic pressure probes at Politecnico di Milano. The sensor denoted as CYL1 has been chosen for this work, given its geometrical simplicity (see figure 1 for details) and the availability of experimental data. The probe is set to measure the total pressure. CYL1 features a relatively simple geometry, which was shown to be properly represented by a 2D model, by virtue of comparisons with experimental data [10]. For this reason, CYL1 was chosen as case study in order to provide a fast tool to study the acoustic behaviour of line-cavity systems when employing non-ideal fluids. Figure 1 provides a 2D representation of the computational domain for CYL1 simulations. Experimental data regarding the CYL1 step response are available from reference [10]. The probe was equipped with a square shaped sensor membrane of 0.9 mm and covered by a RTV coating. The cavity diameter is 1.4 mm, the length of the line is 0.2 mm, whereas the line diameter is 0.3 mm. A corrected line width of 0.236 mm is used for 2D numerical simulation so that the actual cross sectional area is preserved.

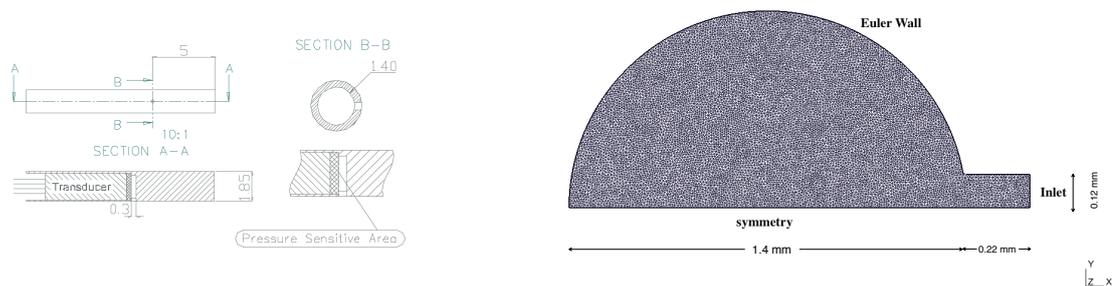


Figure 1. CYL1 geometry from reference [10] and its 2D representation for the CFD simulations.

2.1. Available methods for the prediction of the step response

Since in the configuration of interest here the piezoresistive transducer is encapsulated within the probe head, the fluid dynamics of the resulting line-cavity system is of major importance to determine the overall dynamic characteristics. Apart from experimental assessments, there exist several techniques to estimate the fundamental parameters which characterize the step response

of an aerodynamic pressure probe, such as analytical methods and numerical simulations of different fidelity levels. The latter is chosen to simulate and analyze the step response when working with non-ideal fluids, although analytical models may also be addressed to interpret CFD results.

Line-cavity systems are usually modelled as Helmholtz resonators, which behave as second-order linear systems. However, available analytical models fail to predict the dynamic characteristics of CYL1, whose response was found to be associated to an over-damped second order dynamic system or a first order dynamic system [10]. The geometrical assumptions upon which analytical models rely are indeed not fulfilled for the geometry considered here, as the line is much shorter than the axial dimension of the cavity. When the cavity filling process is predominant with respect to the oscillating behaviour of the line, a first-order step response can be predicted according to the resistor-capacitor circuit analogy [29], where the line impedance $R = \rho_0 c_0 / S_n$ is the resistance and the capacity is $C = V / (\rho_0 c_0^2)$. Here, V represents the cavity volume and S_n the line cross section. The thermodynamic reference quantities are the speed of sound c_0 and the density ρ_0 , which are assumed to remain constant during the process and correspond to the operating condition values. As the flow is initially at rest, ρ_0 and c_0 represent a reference both for total and static quantities and they will be denoted by the subscript 0 throughout the paper. The speed of sound is defined as $c^2 = (\partial P / \partial \rho)_s$, where s is the specific entropy per unit mass. The resulting time constant is given by:

$$\tau = \frac{1}{RC} = \frac{V}{S_n c_0}, \quad (1)$$

The driving parameter for the line-cavity system dynamic characterization is the speed of sound, therefore molecular complexity of the fluid is expected to play a significant role to define the step response. The expression (1) is referred to as acoustic model (AM). The AM provides a fair approximation of CYL1's step response if the pressure perturbation is limited. This means that a high ratio between the external pressure to be measured (p_{ext}) and the operating pressure (p_0) $\beta = p_{\text{ext}} / p_0$ causes significant departures from AM predictions due viscous and thermal effects and possibly to pressure losses ascribable to non-linear wave propagation and turbulence. The working fluid is also expected to influence the validity of the AM, since second-order thermodynamic effects may become relevant compared to the dilute gases case.

Unsteady CFD simulations can be employed to simulate the entire characterization experiment, as they predict the flow field on the overall domain. CYL1's peculiar geometry is exploited to carry out 2D simulations, reducing considerably the computational cost. The open-source CFD software SU2 is considered for this work.

2.2. Numerical simulations for dilute air at room temperature

As a first step towards the simulation of non-ideal compressible flows inside the pressure probe CYL1, the capability of the open-source code SU2 [19, 20] to accurately address this unsteady problem is first assessed. To this end, a simulation is carried out for air, modelled as a PIG. The numerical results are assessed against the available experimental data. The experimental setup used during the dynamic calibration of CYL1 (originally performed in the low-pressure shock-tube of Politecnico di Milano) is reproduced: the operating condition (low pressure section) prescribes a pressure of 1 bar and a temperature of 290 K. The high pressure section of the shock tube is about 2 bar, resulting in a nominal shock wave of 0.5 bar, which corresponds to a total pressure jump of 0.59 bar. However, the measured total pressure perturbation is 0.31 bar, resulting in a total pressure ratio $\beta = 1.31$. This is mainly due to the partial opening of the diaphragm [21]. Given that CYL1 was tested for measuring stagnation conditions, a Riemann boundary condition consisting in the definition of the total pressure and the total temperature is applied at the probe inlet. The total temperature is found via Rankine-Hugoniot relations

and thermodynamic model expressions. At the initial time, the boundary condition represents a finite thermodynamic perturbation, namely a shock wave. Three unstructured meshes have been tested (10 000, 25 000 and 50 000 elements) and three time-step intervals are used ($0.1 \mu\text{s}$, $0.05 \mu\text{s}$ and $0.025 \mu\text{s}$) for both Euler and Navier-Stokes simulations. The latter have been carried out by employing the Spalart-Allmars turbulence model [20]. The dual-time-stepping technique is applied to address the unsteady simulation, where a second-order Roe scheme is applied for the spatial integration of the convective terms, the Averaged Gradient method is used for the computation of the viscous terms and the Backward Euler scheme is adopted for the integration in time.

A fair convergence is obtained both for Euler and Navier-Stokes simulations. The viscous contribution was found to be negligible as in [10], thus only Euler simulations are performed for MDM.

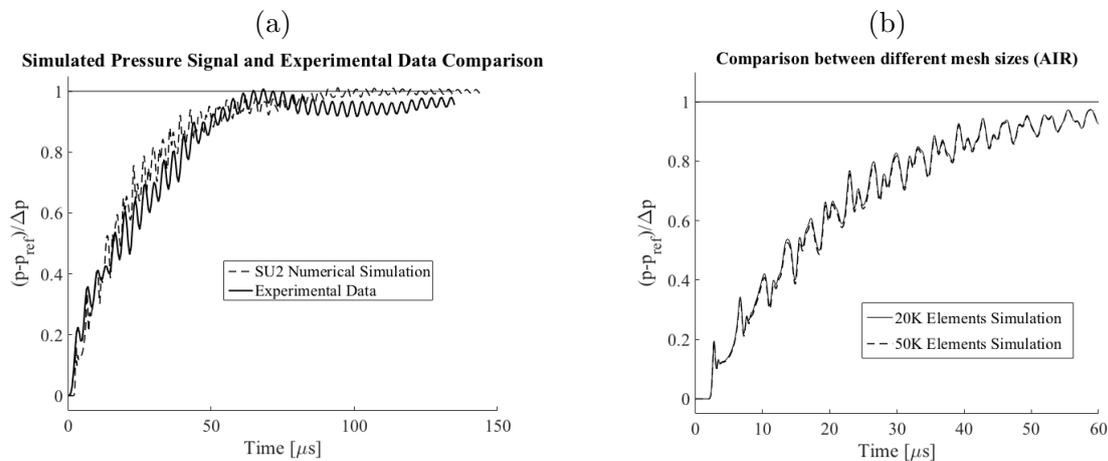


Figure 2. (a) Two dimensional SU2 Euler simulation (performed with the finer mesh of 50000 elements and time-step $0.05 \mu\text{s}$) compared to experimental data available from reference [10, 30] (sampling time is $0.5 \mu\text{s}$). Non dimensional values of the pressure at the center of the cavity are reported. (b) Comparison between numerical simulations performed with different mesh sizes.

Euler simulations results are compared with experimental data in figure 2a. A good agreement is observed as far as settling time and high frequency behaviour are concerned. Small differences can be observed once the pressure signal reaches the step value. This discrepancy is consistent with the fact that the experimental data is affected by the shock tube fundamental harmonic (about 5-10 kHz) [21, 30]. Different mesh sizes consistently reproduce the experimental data, as shown in figure 2b. A first-order linear identification is carried out for the pressure step response by adopting the least square method, resulting in a time constant value of $21.3 \mu\text{s}$, whereas the AM gives $19.1 \mu\text{s}$. This difference may be imputed to viscous, thermal and possibly non-linear effects that are not taken into account by the acoustic approximation.

3. Non-ideal effects in fast-response pressure probes

Non-ideal effects in fast-response pressure probes have three major interplaying sources, namely non-linear wave propagation, turbulence and thermodynamic non-linearity. The latter can be modelled by considering complex thermodynamic models accounting for non-ideal fluid effects.

3.1. Thermodynamic models

Thermodynamic models are needed in compressible-fluids CFD simulations to provide relations that connect pressure, temperature and transport parameters to the fluid-dynamic conservative

variables (density, momentum density and total energy density). The majority of CFD software employs the perfect gas law (PIG) which is based on the assumptions of dilute gas. The PIG model has been proven to be reliable for a large range of engineering applications, though from textbook thermodynamics it is well known that all fluids exhibit non-ideal behaviour in the close proximity of the saturation curve, the compressibility factor $z = Pv/RT$ being significantly different from unity. More accurate thermodynamic models must be employed in these conditions to properly describe the fluid properties. Cubic equations of state (EoS) such as the PRSV model [31], allow more accurate predictions of non-ideal phenomena. The behaviour of the fluid is related to the value of the fundamental derivative of gas-dynamic [32], defined as

$$\Gamma = 1 + \frac{\rho}{c} \left(\frac{\partial c}{\partial \rho} \right)_s. \quad (2)$$

The fundamental derivative is usually greater than unity ($\Gamma = (\gamma + 1)/2$ for perfect gases, where γ is the ratio of the specific heats), though regions where $0 < \Gamma < 1$ or even $\Gamma < 0$ are near the saturation curve, giving origin to non-ideal and non-classical phenomena, such as rarefaction shock waves [17]. The value of Γ is expected to play a major role on the dynamic response of the pressure probe, since it is intimately related to the rate of variation of the speed of sound due to pressure perturbations. Hence, the PIG model can possibly deliver unaccurate results concerning the response of the sensor for certain operating conditions, while non-ideal model may provide more reliable final results, at the cost of increased computational effort.

The PRSV model has been recently introduced within the SU2 environment [20]. The model is defined by the following relations:

$$P(T, v) = \frac{RT}{v - b} - \frac{a\alpha^2(T)}{v^2 + 2bv - b^2} \quad \text{and} \quad e(T, v) = \phi(T) - \frac{a(k + 1)}{b\sqrt{2}} \alpha(T) \tanh^{-1} \frac{b\sqrt{2}}{v + b} \quad (3)$$

where pressure P and internal energy per unit mass e are expressed as functions of the specific volume v and the temperature T . R is the gas constant and $\phi(T) = \lim_{v \rightarrow \infty} e(T, v)$ is the internal energy per unit mass in dilute conditions. The coefficient a represents the action of inter-molecular forces and b is the co-volume. A complete definition of all parameters can be found in [31]. They depend on several quantities, such as critical pressure ($p_c = 14.15$ bar), critical temperature ($T_c = 564.1$ K), acentric factor ($\omega = 0.529$), gas constant ($R = 35.2$ J/kg/K) and reference specific heat ratio ($\gamma_\infty = 1.018$).

3.2. Non-ideal effects on the dynamic characterization of the pressure probe

The AM (1), discussed in section 2.1, provides estimates of the time constant describing CYL1's step response, which will be later shown to agree well with the CFD simulation results. However, non-linear effects might cause a large departure from the estimation of the model, due to pressure losses associated to non-linear wave propagation within the feeding line and to thermodynamic properties variations within the cavity. Density and speed of sound variations are expected to play the most relevant role for distinguishing the pressure probe step response when working with air and MDM. Thermodynamic derivatives

$$\left(\frac{\partial c}{\partial P} \right)_s = \frac{\Gamma - 1}{\rho c} \quad \text{and} \quad \left(\frac{\partial \rho}{\partial P} \right)_s = \frac{1}{c^2}$$

suggest that peculiar values for the initial reference state, the molecular complexity and the fundamental derivative of gas-dynamic may possibly lead to departures from the linear AM (1). By simple differentiation it can be inferred that density and speed of sound variations act in opposite directions, since an increase of density is expected to delay the response, whereas an increase of the speed of sound is expected to accelerate it. In the following section, numerical simulation results will be addressed with the aid of these considerations and differences between thermodynamic models will be highlighted.

4. Dynamic characterization results

Simulations have been performed with unstructured meshes of 10 000, 20 000 and 50 000 elements to ensure convergence in space, while time-step intervals of 0.1 μs , 0.25 μs and 0.5 μs were tested to ensure convergence in time.

4.1. MDM and air response comparison under the PIG model

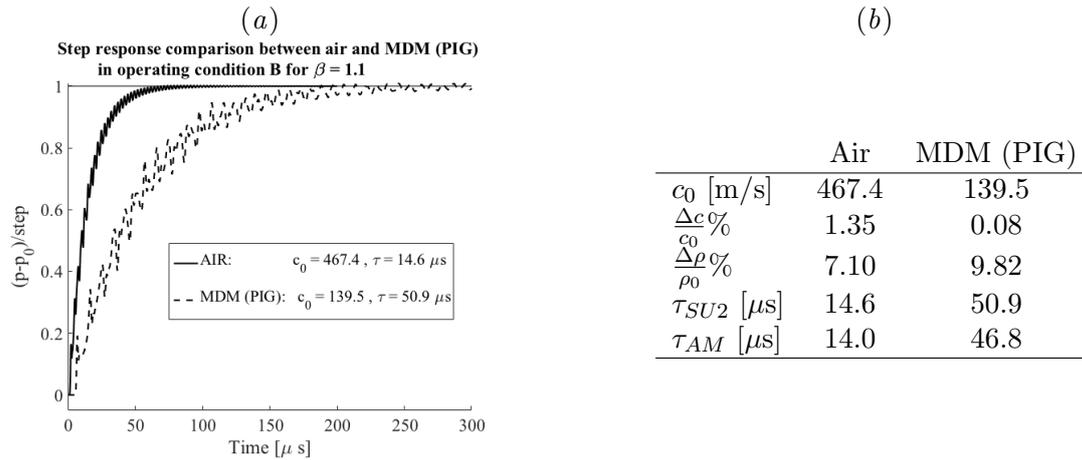


Figure 3. Comparison between the step response of air and MDM (PIG model) in operating condition B for a pressure perturbation $\beta = 1.1$. The percentage variations of speed of sound and density are computed by considering the values of the perturbed state and the reference values (e.g. $\Delta c = c_{\text{ext}} - c_0$).

Figure 3 compares the simulated step response of CYL1 when employing air and MDM, both modelled as ideal gases. The operating condition is state B (reported in table 1) for both fluids and a perturbation $\beta = 1.1$ is applied. Both responses are typical of a first-order system, which indicates that molecular complexity does not affect the qualitative characteristics of the flow field inside the pressure probe. However, the time needed to reach the step value is very different. Indeed, first-order system identification gives $\tau = 14.6 \mu\text{s}$ for air and $\tau = 50.9 \mu\text{s}$ for MDM, while the AM gives $\tau = 14.0 \mu\text{s}$ and $\tau = 46.8 \mu\text{s}$. Molecular complexity implies lower speed of sounds for MDM, thus its step response is much slower, as expected. The relative difference between the actual time constant and the AM prediction is higher for MDM than for air. This might be explained by considering again the higher molecular complexity of MDM with respect to air: speed of sound variation of MDM is indeed extremely limited ($\Gamma \rightarrow 1$) and its influence in compensating the density increase is negligible with respect to air.

Op. Cond.	β	c_0 [m/s]	$\frac{\Delta \rho}{\rho_0}$ %	$\frac{\Delta c}{c_0}$ %	τ_{SU2} [μs]	τ_{AM} [μs]	Error %
A	1.23	144.5	22.94	0.19	53.5	45.2	15.6
B	1.23	139.5	22.92	0.17	55.5	46.8	15.7
B	1.1	139.5	9.82	0.08	50.9	46.8	8.02

Table 2. Comparison between the step response results of MDM modelled as a PIG.

Table 2 reports selected results concerning three different simulations performed with MDM. It can be inferred that the operating conditions poorly influence the step response when working with high molecular complexity fluid modeled as ideal gases. This is a direct consequence of

the fact that $\Gamma \rightarrow 1$, thus the speed of sound is similar even for different operating conditions. The time constants provided by the simulations in operating conditions A and B with the same perturbation $\beta = 1.23$ are indeed very similar. Moreover, the error with respect to the AM is identical, again stressing the concept. As expected, by considering the same operating condition (B) and two different pressure perturbations ($\beta = 1.1$ and $\beta = 1.23$), the relative error with respect to the AM is higher for the latter, as non-linear effects are greater.

4.2. PIG model vs PRSV model simulations

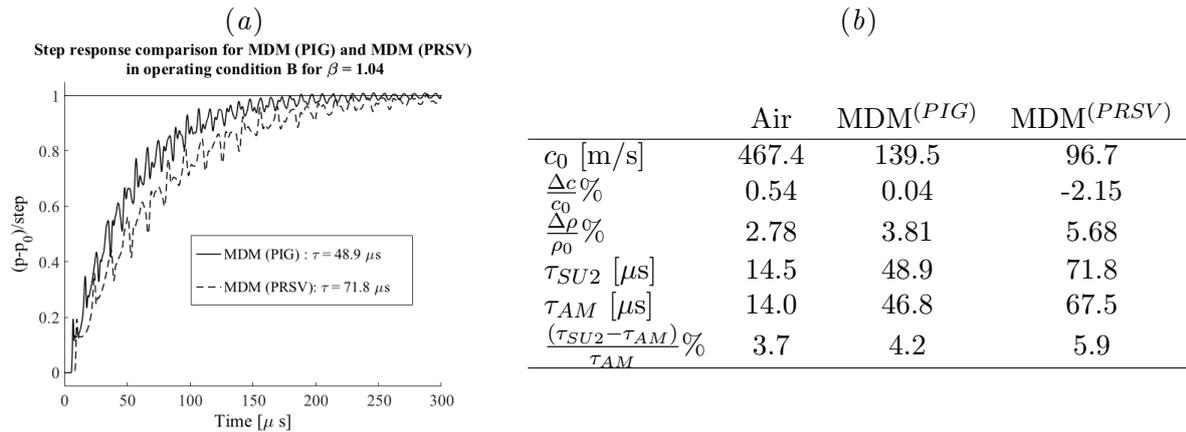


Figure 4. Comparison between MDM (described as an PIG) and MDM (described as a PRSV gas) in operating condition B for $\beta = 1.04$. Results for air in the same conditions are also shown.

Figure 4a reports the CYL1's step response of MDM modelled by means of PIG and PRSV models in operating condition B for $\beta = 1.04$. Table 4b reports the thermodynamic properties variations and the time constants. It is remarkable that the AM provides fair predictions, since the acoustic approximation becomes more and more accurate as the pressure perturbation decreases. A slightly larger error is observable for the case of MDM modelled as a PRSV gas, which might be due to the more pronounced density variation. It should be noted that PRSV model gives a completely different value of c_0 with respect to the PIG model, suggesting that in these operating conditions non-ideal effects are non negligible.

When β increases, the differences between the PIG and PRSV models simulations become greater, as figure 5a demonstrates. Step responses are reported for operating condition B, $\beta = 1.23$ and $\beta = 1.2$. The derived time constants are $\tau = 55.5 \mu s$ and $\tau = 84.4 \mu s$, while the errors with respect to AM predictions are 15.5% and 20%, respectively. This suggests that if the PIG model is employed, the performances of the pressure probe in terms of frequency response are overestimated for two main reasons, namely the overestimation of the speed of sound value in the actual operating condition and the underestimation of the speed of sound variation due to the pressure perturbation. The fundamental derivative of gas-dynamic computed by means of PRSV model relations is indeed very different from unity in operating condition B ($\Gamma = 0.63$) and its value precludes to a reduction of the speed of sound, which causes the step response to be slower. This effect could become dramatic as β increases. For instance, a perturbation $\beta = 1.37$ in operating condition B cause a difference with respect to the AM prediction as high as 33%. The operating conditions are indeed very important for the dynamic characterization. The last example is figure 5b, which reports the step response of MDM described as a PRSV gas in operating condition A and B for $\beta = 1.2$. The differences between the two responses are quite large and the differences with respect to the AM predictions are at odds, since in

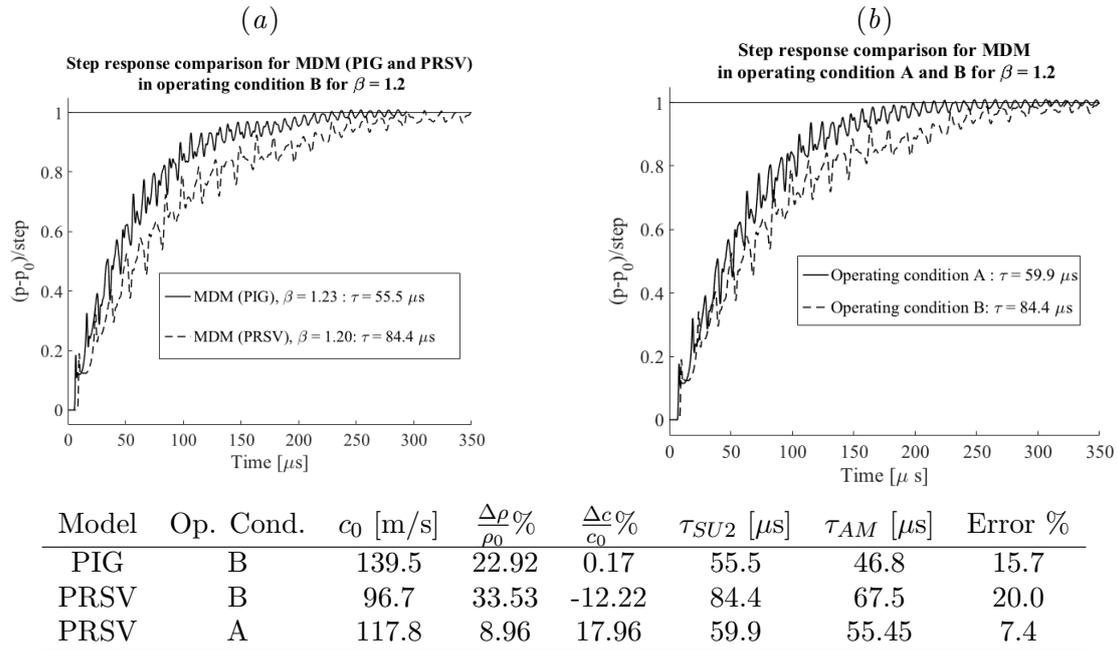


Figure 5. (a) Comparison of the step responses between MDM (described as PIG) and MDM (described as PRSV gas) in operating condition B for $\beta = 1.23$ and $\beta = 1.2$, respectively. (b) Comparison between MDM (described as PRSV gas) in operating condition A and B for $\beta = 1.2$.

operating condition A the line impedance augmentation (caused by the density increase) is almost compensated by the speed of sound increase within the cavity.

5. Conclusion

The dynamic calibration of a selected fast-response aerodynamic pressure probe working with flows in non-ideal regime has been addressed. The open source CFD software suite SU2 has been used to simulate the flow field inside the probe, which can be configured as a line-cavity system. Thanks to the availability of experimental results from reference [10], it has been possible to assess the SU2 simulations through comparison. The NCFD solver of SU2 has been exploited to simulate dynamic characterization experiments with siloxane MDM. Both the constant-specific-heat ideal gas (PIG) and the Peng-Robinson-Stryjek-Vera (PRSV) models have been considered to describe the fluid and results have been compared. The step response of the probe is typical of a first-order system, thus the system time constant has been considered as a representative variable to compare the results.

Both models deliver higher time constants for MDM with respect to air for the same pressure perturbation and operating condition. This is possibly due the relatively low value of the speed of sound, because of the molecular complexity of MDM is higher. Molecular complexity plays also a role in determining the departure of the actual time constant from the AM predictions: for a fixed β , non-linear effects play a stronger role as molecular complexity increases.

Two main observations can be made by comparing the two considered thermodynamics models. These are the different operating speed of sound that the models predict and the different rates of variation of the thermodynamic properties during the filling process. Even if the former was somehow corrected by means of an *ad hoc* choice of the specific heat ratio (something that is not always possible, because $\gamma > 1$ from thermodynamic stability), the latter cannot be addressed if the PIG model is retained. PIG model results are particularly

questionable in regions where Γ goes below unity. Non-ideal regime ($\Gamma < 1$) and low-speed-of-sound regions (such as operating condition B) appear to be the most critical configuration for the application of fast-response pressure probes, as the combined effects of density and speed of sound variations cause a huge increase of the system time constant.

Acknowledgments

This research is supported by ERC Consolidator Grant N. 617603, Project NSHOCK, funded under the FP7-IDEAS-ERC scheme.

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