ENGINEERING DESIGN OF AN ELECTRONIC FLOW TRANSDUCER BASED IN A VENTURI DIFFERENTIAL PRESSURE DEVICE

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Resumo

Este artigo apresenta um estudo sobre o desenvolvimento de um medidor de vazão baseado no tubo de Venturi como elemento primário. O projeto do transdutor é descrito de acordo com seus detalhes dimensionais e construtivos, auxiliado por resultados provenientes de simulações numéricas. Algumas características do projeto do transdutor são descritas neste trabalho, como construção em câmaras para se obter pressão média. Um projeto eletrônico preliminar para o Venturi é também apresentado neste artigo, considerando o uso de um transdutor comercial para medição de vazão por diferença de pressão, incorporado ao Venturi. Um planejamento experimental para calibração estática é discutido, a fim de determinar características relacionadas à mudança do coeficiente de descarga com o número de Reynolds e à razão de diâmetro. Aplicações futuras do Venturi proposto serão feitas para medição de vazão com líquidos e gases, com a finalidade de validar o projeto proposto como um medidor de vazão comercial.

Palavras-chave*: Venturi, instrumentação, escoamento.*

Abstract

This paper presents a study on the development of an electronic flowmeter based in a Venturi tube as primary element. The design of the transducer is described with respect to its dimensional and constructive details, aided by computational flow simulation results. Some design characteristics of the transducer are described in the paper such as built in chambers for pressure averaging. A preliminary electronic design for the Venturi transducer is also presented in the paper, considering the use of a commercial transducer for differential pressure measurement, incorporated to the Venturi body. An experimental planning for static calibration is discussed in order to determine characteristics related to discharge coefficient change with Reynolds number and contraction ratio. Future applications of the proposed Venturi transducer will be made for flow rate measurements in actual applications both in liquid and gas phases, in order to validate the proposed design as a commercial flow measurement product.

Keywords*: Venturi, instrumentation, flow.*

1 Introduction

Flow meter devices based on pressure drop elements are largely used in several different applications such as natural gas processing, pipeline transport of multiphase mixtures in the petroleum industry, mixtures of oils, water and gas produced from wells, etc. Among the devices available for pressure drop based flow measurements, Venturi tubes represent a simple and cost effective solution. However, in spite of its general application, Venturi elements are still of limited use, being restricted to application where accuracy is not the main concern.

Recently, with the expansion of natural gas use in Brazil, especially in those regions not served by gas distribution network, an important demand on low cost accurate means for gas consumption monitoring has occurred. Although there are different commercial measurement solutions for such flow monitoring task in the market, they are all based in imported technologies and have high relative cost. Then, there is both a need and opportunity for applied technological research leading to national flow measurement products answering the industry needs.

Although Venturi tubes are very simple and well known primary elements for flow rate measurements, a complete understanding of fluid flow phenomena trough Venturi tubes is far from being accomplished. With the improvement of instrumentation, hardware and software tools, the study on Venturi tubes, as in other fields, has produced several recent publications, staying an active field of research.

Flow measurement of two-phase by differential pressure elements has motivated different researches (AMINA and OWENA, 1995; BOYER and LEMONNIER, 1996; PALADINO and MALISKA, 2002). Applications such as wet gas flow measurement occurring for example in natural gas processing, requires special correlations for the discharge coefficient (SKEA and HALL, 1999; STEVEN, 2002; ELPERIN, FOMINYKH and KLOCHKO, 2002).

Even in the case of single-phase flows, the occurrence of mixtures, as for instance water-oil, can affect in a significant way the performance of a flow meter, requiring an special approach (SKEA and HALL, 1999). Another aspect is related to flow measurements of gases (NAKAO, YOKOL and TAKAMOTO, 1996;JITSCHIN, RONZHEIMER and KHODABAKHSHI, 1999; HAYAKAWA et al, 2000).

With respect to the dimensional design of primary differential pressure flow rate elements, such as the Venturi tube, the influence of geometrical and constructive aspects outside standard definitions has been considered in several works (PARK, 1995; LAWS and OUAZZANE, 1995; ISHIBASHI and TAKAMOTO, 2000; READER-HARRIS et al, 2001).

Another aspect of critical importance for accurate measurements is related to the flow conditions upstream the differential pressure flow element. In this field, researches are being carried out in order to investigate the performance of different flow conditioners (ERDAL, 1997; FRATTOLILLO and MASSAROTTI, 2002; PIMENTA and MARTINS, 2003).

However, in spite of all the related research work, two research topics still almost unexplored: flow measurement of refrigerant fluids in refrigeration systems and the engineering design of differential pressure based electronic flow transducers. In the refrigeration field, some aspects such as, superheating and subcooling degrees influence in the persisting existence of liquid drops and gas bubbles and influence of lubricant compressor oil mixed with refrigerant, in flow measurement accuracy (PIMENTA, 1997; DE LIMA, PIMENTA and HERNANDEZ, 1998) requires much more investigations.

2 Flow Measurement Aspects

One of the most widely used flow meter principle involves the use of a fixed area flow restriction in a pipe or duct in order to cause a pressure drop varying with the flow rate. In this section, basic considerations related with Venturi tubes for flow measurements are presented.

The choice for a Venturi in the present work is due to the fact that it allow some economical advantage with respect to other pressure drop meters (as orifice plates for example) in measuring larger flow rates, where power losses and operating costs may be reduced.

2.1 Venturi Flow Fundamentals

Venturi tubes, Fig. 1, as other pressure drop meters finds great application, mainly because of its simplicity, its low cost and great volume of data available for predicting its behavior.

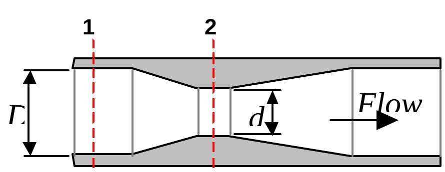

Figure 1. Basic Venturi configuration

In the case of one-dimensional, incompressible, frictionless fluid flow without heat transfer or elevation changes, energy and mass conservations principles applied to the fluid between sections 1 and 2, allow to express volume flow rate, after some substitutions, we find:

$$\dot{V}_{th} = \frac{\pi \cdot d^2}{4} \cdot \frac{1}{\sqrt{1-\beta^4}} \cdot \sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

or in terms of mass flow rate, multiplying each side of Eq. (1) by the fluid density,

$$\dot{m}_{th} = \frac{\pi \cdot d^2}{4} \cdot \frac{1}{\sqrt{1-\beta^4}} \cdot \sqrt{2\Delta p \rho} \tag{2}$$

where,

$\dot{V}_{th}$	theoretical volumetric flow rate	[m³/s]
$\Delta p = p_1 - p_2$	pressure drop between sections 1 and 2	[Pa]
$\beta = D/d$	diameter contraction ratio	[-]
D	inlet diameter at section 1	[-]
d	throat diameter at section 2	[-]
ρ	fluid density	[kg/m³]
$\dot{m}_{th}$	theoretical volumetric flow rate	[kg/s]

In actual applications, deviations from theoretical model given from previous equations will occur requiring some kind of correction. This is commonly taken into account by means of a discharge coefficient C_d, obtained after experimental calibration, basically as a function of the Reynolds number (Re_D), and defined as the ratio between actual ($\dot{m}$) and theoretical flow rate so that,

$$\dot{m} = C_d \cdot \dot{m}_{th} \tag{3}$$

In the case of compressible fluids, besides the energy and mass conservation equations, it is also necessary to consider an equation of state relating the intensive properties of the fluid – temperature, pressure and density. In this case, Eqs. (1) to (2) are modified by the introduction of a new correction factor to take effects of compressibility into account. This refers to the use of a compressibility factor ε, introduced in previous equations, to compute mass flow rate as,

$$\dot{m} = C_d \cdot \varepsilon \cdot \frac{\pi \cdot d^2}{4} \cdot \sqrt{\frac{2\Delta p \rho}{1-\beta^4}} \tag{4}$$

A simplified representation of the compressibility factor can be obtained by considering ideal gas behavior and an isentropic process between states 1 and 2, which allow to write,

$$\varepsilon = \left[\left(\frac{k r^{2/k}}{k-1}\right)\left(\frac{1-\beta^4}{1-\beta^4 r^{2/k}}\right)\left(\frac{1-r^{(k-1)/k}}{1-r}\right)\right]^{\frac{1}{2}} \tag{5}$$

where, k is the gas isentropic exponent and r is the pressure ratio defined $r=p_2/p_1$.

2.2 Flow Measurements Standards

International standard ISO 5167-1:1991 in its Brazilian version NBR ISO 5167-1 are the main code for reference in measurement of fluid flow by means of pressure differential devices, such as orifice plates, nozzles and Venturi tubes.

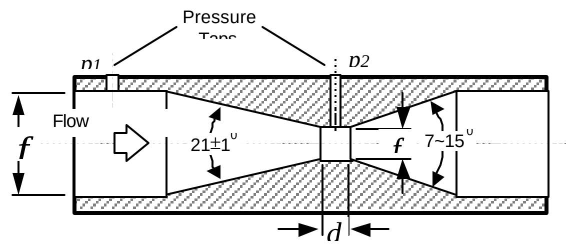

Figure 2. Classical Venturi tube standard dimensions

With respect to machined classical Venturis, Fig. 2, the Standard applies for *d*, β and Re_D ranging from 50 to 250 mm; 0.40 to 0.75, and 2.10^5 to 10^6, respectively. For such conditions a standard Venturi can be used assuming a C_d=0.995, with an uncertainty on this value about 1.0 %. Otherwise, the Standard establishes that effects of β, Re_D and k/D on C_d are not well known.

According the standard, the compressibility fator ε, can be calculated by means of Eq. (4), with pressure ratio limited to $r \geq 0.75$, and with reference to flow conditions at section 1. The uncertainty in this determination of ε is said to be equal to $2.(4+100\ \beta^8).Dp/p_1$.

The Standard also imposes some constraints with respect to the straight pipe length required upstream the Venturi meter. Such a constraint is related with the fact that standard calibration data assume no significant flow disturbances such as may be caused by elbows, bends, tees, valves, etc. The presence of such upstream disturbances close to the Venturi can invalidate standard, as well as, experimental calibration data, causing significant errors. Then, care must be taken when mounting a Venturi meter, by observing minimum distances of straight pipe required upstream the Venturi accordingly the existing flow perturbation.

When minimum distances are not feasible, flow conditioners must be adopted and mounted upstream the Venturi in order to smooth out the flow. With respect to this possibility, the standard recommends some different types of flow conditioners devices allowing using shorter pipe lengths between the flow disturbance element and the Venturi.

3 Engineering Design

3.1 Venturi Basic Construction

Figure 3 shows the mechanical design adopted to the Venturi meter. The basic geometry adopted is in agreement with NBR ISO 5167-1 and reflects the recommended dimensions for a Classical Venturi type with inlet (*D*) and throat diameter (*d*) of 50 and 25 mm respectively.

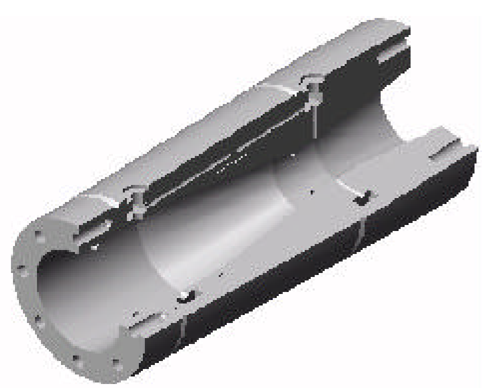

Figure 3. Mechanical construction of the Venturi transducer

Some particular aspects of the design are related to: (1) a three parts construction adopted in order to include two piezometric chambers for pressure averaging at each section, (2) a possible interchangeable of the transducer core, allowing change of the contraction factor, (3) a built-in pressure sensor for pressure drop measurement and (4) flanged connections at both ends for easy mounting at different installations.

3.2 Flow Conditioner Design

One important concern for adequate performance of the Venturi flow transducer is related to the strong influence of the fluid velocity profile on the flow measurement. This is normally solved with the use of some flow conditioner device installed upstream the flow meter. Such a flow conditioner reduces the effect of flow perturbations such as swirl, cross-flow, and asymmetry can produce relevant systematic errors, while allowing more compact installations.

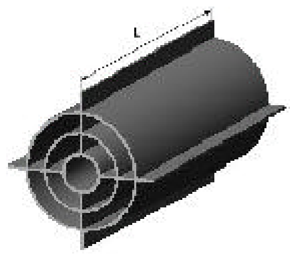

Figure 4. Flow conditioner adopted for the Venturi transducer

Several different flow conditioner devices are available being classified in two main groups (FRATTOLILLO and MASSAROTTI, 2002): turbulent mixing and whirling action conditioners. In this work, a New design flow conditioner which has shown, from numeric analysis, a good performance, particularly with respect to swirl attenuation (PIMENTA and MARTINS, 2003) was adopted. Figure 4 presents a view of this new flow conditioner.

Two kind of absolute efficiency parameters (FRATTOLILLO and MASSAROTTI, 2002) are considered, in order to evaluate conditioner performance: flatness efficiency parameters, K_f and K_{fm} and, axial vortex efficiency parameters, K_v and K_{vm}, The flatness efficiency parameters measure the difference between the effective distorted and the fully developed velocity profile being important for instruments affected by the flow velocity profile, as the in the case of Venturi flow meters. The axial vortex efficiency parameters measure the intensity of the axial vortex and are very important in the flow meters influenced by swirl.

Figures 5 and 6 presents the change of flatness and axial vortex efficiency parameters, respectively, as numerically computed along the flow axis *z*, from conditioner outlet where *z/D*=0 (PIMENTA and MARTINS, 2003). These results allow comparing the performance of the New conditioner against the classical Etoile conditioner, as well as, with the situation when no flow conditioner is used. Both the New and the Etoile conditioners have a length of 2D.

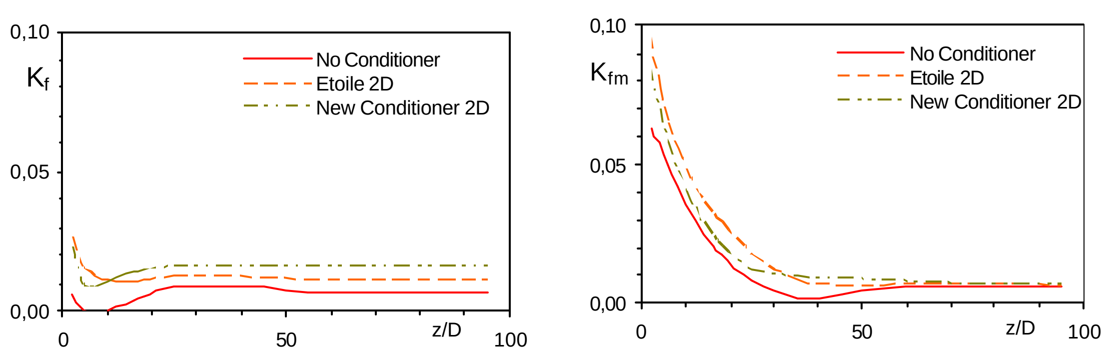

Figure 5. Flatness efficiency parameters K_f and K_{fm} (PIMENTA and MARTINS, 2003)

Analyzing the values for parameter K_f, we see that the Etoile 2D conditioner has a better efficiency after z/D=20D. In terms of the angular momentum K_{fm}, the New conditioner presents a better efficiency up to a distance of 35D. With respect to axial vortex parameters K_v and K_{vm}, the New conditioner presents better efficiency than the Etoile 2D conditioner, with a significant vortex reduction at 10D with the New conditioner. On the other hand, the Etoile 2D conditioner has the same swirl number K_{vm} as the New conditioner after a distance of 40D.

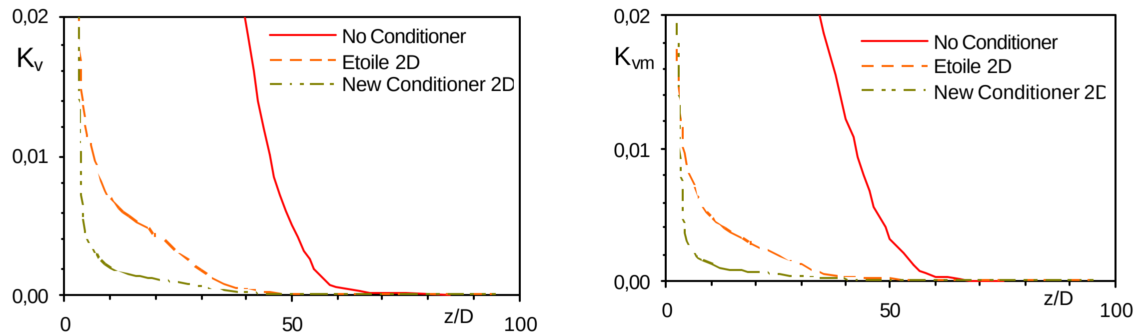

Figure 6. Axial vortex efficiency parameters, K_v and K_{vm} (PIMENTA and MARTINS, 2003)

Then, with respect to vortex reduction, the New conditioner is adequate having performance similar to the Etoile conditioner, since after each conditioner outlet there is a vortex intensity quite reduced when comparing with the case when no conditioner is used.

3.3 Theoretical Discharge Coefficient

In order to get some insight on the discharge coefficient for the Venturi designed, a CFD simulation using a commercial software (CFX – Solver Manual, 2002) and a modeling and simulation technique previously developed (PIMENTA and MARTINS, 2003) was performed.

Figure 7 presents the main numerical results of the change in discharge coefficient with Reynolds number for the Venturi prototype, using water as the measuring media. A typical change is obtained for different diameter contraction ratios. The Venturi was placed at a distance of 6D from a double elbow perturbation (PIMENTA and MARTINS, 2003). A flow conditioner was not used in this case.

These results are also in good agreement with literature. The averaged discharge coefficient was of around 0.955 for the Reynolds number of $2x10^5$. As can be taken from Holman (HOLMAN, 2000) for the same condition of construction of the Venturi (β=50 mm/ 25 mm) and for the above mentioned Reynolds number the discharge coefficient is 0.97, resulting in a deviation of about 1,5 %.

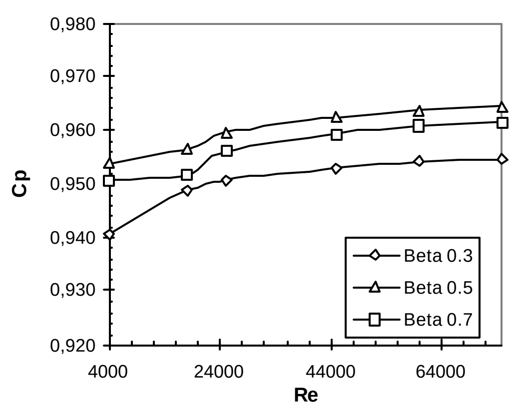

Figure 7. Numerical change in discharge coefficient with Reynolds number using water

Table (1) presents some preliminary numerical results for the discharge coefficient using methane (CH_4) gas, as measuring fluid, for a range of Reynolds numbers corresponding to typical flow velocities inside pipes.

The main differences with respect to the water simulation case is related to the use of an ideal gas model for fluid properties and the assumption of a velocity profile at the inlet upstream the elbows. The pipe physical configuration is the same as described for the simulation with water.

Table 1. Numerical results for methane flow thought a classical Venturi tube, as in Fig. 1, with β = 0.5.

Re [-]	ΔP [Pa]	$\dot{m}_{th}$ [kg/s]	$\dot{m}$ [kg/s]	C_d [-]	r [-]	ε [?-]
4479	5,643	0,001677	0,00133	0,79294	0,99994	0,99996
11197	35,525	0,004209	0,00333	0,79142	0,99965	0,99978
33592	317,497	0,012582	0,00999	0,79558	0,99687	0,99803
55987	889,655	0,021061	0,01669	0,79686	0,99124	0,99449
78381	1712,139	0,029217	0,02342	0,81017	0,98318	0,98940
100776	3165,421	0,039727	0,03028	0,77744	0,96899	0,98041

3.4 Differential Pressure Measurement

Differential pressure between taps 1 and 2 will be measured with a commercially available pressure transducer based on a micro-machined silicon pressure sensor with stress free packaging techniques to provide accurate, temperature compensated and amplified signal corresponding to differential pressure measured.

The pressure transducer requires external power excitation providing a voltage output in proportion to this excitation and pressure input. Then, a circuit for power excitation from a DC regulated source will be built allowing also a battery operation. Additionally an optional circuit for conditioning of output signal will also be included for the Venturi. Figure 8 presents the electronic circuit for the Venturi transducer.

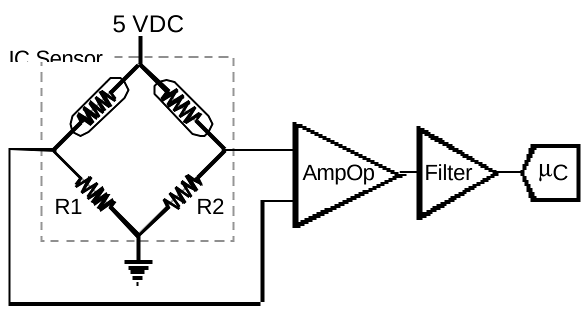

Figure 8. Electronic scheme for the Venturi transducer

As it is observed in the Fig. 8 the small differential output of the bridge integrated circuit sensors is gained and converted from differential to single ended with an instrumentation operational amplifier (AmpOp). The signal then passes through a low pass filter. The low pass filter eliminates out-of-band noise and unwanted frequencies in the system before the microcontroller takes the operation of further calibration and translation if it is needed to be for display purposes.

The differential pressure transducer and its circuit will be incorporated to the Venturi body after its construction, thanks to a specific mounting design. Two channels of small diameter transmit the averaged pressure from each Venturi tap to the pressure transducer ports, which are fixed to the Venturi body.

4 Venturi Calibration

Application of a Venturi for flow rate measurement is an indirect procedure based in the use of Eq. (2). Mass flow rate is obtained by simply measuring the differential pressure Dp between pressure taps 1 and 2, which is then inserted in Eq. (2), now written as,

$$\dot{m} = C_d \cdot e \cdot K \cdot \sqrt{\Delta p} \qquad (6)$$

where, neglecting fluid density change, a constant K was introduced as,

$$K = \frac{\pi d^2}{4} \cdot \frac{1}{\sqrt{1-\beta^4}} \cdot \sqrt{2\rho} \qquad (7)$$

where $(1-\beta^4)^{-1/2}$ is profile factor depending only on the Venturi geometry.

However, before use, the electronic Venturi meter must be submitted to a static calibration procedure in order to determine its main characteristics related to the discharge coefficient change with Reynolds number and contraction ratio.

The calibration will be performed using the experimental apparatus shown in Fig. 9, specially conceived for flow meter devices testing using water.

Both a direct and indirect method will be used for the calibration. In the direct scheme, reference instruments for force (load cell) and time (computer clock) are adopted in order to obtain the mass flow rate through the Venturi under calibration. On the other side, the indirect method makes use of reference instruments for flow rate (orifice and turbine meter) and temperature (PT100) in order to obtain the mass flow rate.

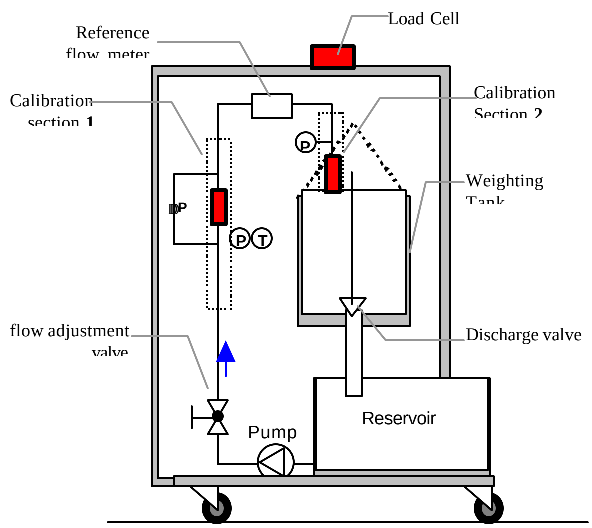

Figure 9. Experimental Apparatus for the Venturi calibration.

Both a direct and indirect method will be used for the calibration. In the direct scheme, reference instruments for force (load cell) and time (computer clock) are adopted in order to obtain the mass flow rate through the Venturi under calibration. On the other side, the indirect method makes use of reference instruments for flow rate (orifice and turbine meter) and temperature (PT100) in order to obtain the mass flow rate.

A calibration for the differential pressure transducer is also required in order to assure accurate measurement. This will be done previously to the Venturi calibration, by an indirect procedure using a hand held type pressure generator and a reference pressure transducer previously calibrated by a primary standard pressure balance.

The Venturi transducer will be also tested for flow rate measurements in two actual applications: a refrigeration unit and a combustion chamber.

In the first application, a chiller test bench using a refrigerant fluid, running at different temperature, pressure and flow rate conditions. The Venturi under test will then be installed at compressor suction line and condenser liquid reservoir outlet, in order to evaluate the Venturi performance under gas and liquid flow rate measurements respectively. Application of the Venturi tube in the chiller test bench will also allow some interesting investigations concerning the influence of lubricant oil mixing with the refrigerant as well as the effect of two-phase flows related to different subcooling and superheating degrees.

In the combustion chamber application, the Venturi prototype will be installed in the fuel supply line of an industrial burner mounted in an existing experimental test bench for combustion studies. In this case, it will be possible to evaluate the Venturi measurement performance with hydrocarbon gaseous fuels such as LPG (liquefied petroleum gas) and natural gas, comparing readings from the Venturi against a reference turbine meter.

5 Conclusions

Basic theory, numerical results, instrumentation aspects and Standard considerations related to the preliminary design of an electronic Venturi flow transducer were presented in this paper.

At this stage the design concept for the Venturi transducer has been developed and numerical results for flow measurement performance were obtained. A planning for the next phases was considered with respect to the design of the electronic conditioning circuit as well as for the experimental study to be carried out after the Venturi construction.

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