PERFECT GAS APPROACH VALIDATION AIMING ESTIMATION OF THERMOPHYSICAL PROPERTIES IN FLARE FLOWS CONSIDERING OPERATIONAL DATA

Alex Salgado, alexluzs@gmail.com
Rogério Ramos, ramosrogerio@hotmail.com
Universidade Federal do Espírito Santo - UFES

Abstract. *The aim of present work is to investigate the possibility and consequences to use the perfect gas modelling in order to predict some thermophysical properties of natural gas flowing in off-shore flare tubes. Such validation will propitiate the development of a fast and realible self-diagnostics software for ultrasonic flowmeter - UFM specific to flare metering. The validation is based on comparision of thermophysical properties simulated by AGA report no. 10 virial state equation (once gas composition and operational pressure and temperature data are known) and those properties obtained by the perfect gas classical approach. Once the thermophysical behaviour is validated, the thermodynamic property speed of sound - SOS may be calculated and used to check ultrasonic gas meters operation.*

Keywords*: ultrasonic flow meter, flare metering, self-diagnostics, sonic speed*

1. INTRODUCTION

The motivation of present work appeared with publication of Portaria Conjunta ANP/INMETRO n^o. 1 (2000) a federal regulation which imposes new challenges for Brazilian companies and institutions which deals with flow metering, especially those users of new technologies, as ultrasonic flow meters – UFM´s. That regulatory mark described, for the first time in Brazil, the conditions and proceedings for operational and fiscal metering of hydrocarbons flows as well as included the utilization of ultrasonic flow meter as a legal and creditable technology for such measurements.

On the other side, the publication of American Gas Association – AGA report no. 9 (1998) diffused information about basic features of ultrasonic technology for gas flow measurement. On those times, AGA-9 text admitted that ultrasonic technology applied to flow metering was still in early stage and suggested that more studies were needed in order to define, with confidence, many features about UFM´s like installation effects, necessity of straight tubes, noise treatments, quality of the velocity profile on the metering section, gas composition influence, etc.

Technological and scientific community answered this challenge with a large number of dedicated conferences and articles about such features effects, like were made by Eren (1998), Lansing (2000, 2002, 2004), Ruppel and Peters (2004) and Raisutis (2006) among others.

An important complement of AGA-9 report came with the publication of AGA report no. 10 (2003), where is described a virial state equation which predicts the speed of sound - SOS for natural gas, having as input data: chemical composition, temperature and pressure. AGA-10 report is probably the most updated and reliable equation to simulate such property with confidence, presenting uncertainties around 0,1% for the range of interest. Other works dedicated to examine thermophysical behavior of natural gas can be found in Burnstein *et al*. (1999) and Estela-Uribe *et al*. (2003).

Due to such efforts, the utilization of ultrasonic flow meters for natural gas applications has grown significantly. Today, virtually every oil company is using such technology, either for custody transfer or operational monitoring. Some benefits of this technology include the following:

- Accuracy: the meters can be calibrated to an uncertainty less than 0.3%;
- Large turndown: typically more than 50:1 (orifice plates offer typical turndowns around 3:1 and turbines, 20:1)
- Tolerant to wet gas;
- Non-intrusive: do not cause pressure drop;
- Low maintenance: there are no moving parts;
- Self-diagnostics: data for determining meter´s healthy is available.

The ability to diagnose the meter´s health is an important feature of UFM´s and this paper discuss and proposes a way to check the operational health of ultrasonic flow meter specifically to flare metering.

Ultrasonics flow measurements developments dedicated to flare applications specifically are found in the works of Mylvaganan (1989) and Folkestad and Mylvaganan (1989, 1993).

2. ULTRASONIC METER BASICS

The basic construction of an ultrasonic flow meter is relatively simple as shown in Fig. 1.

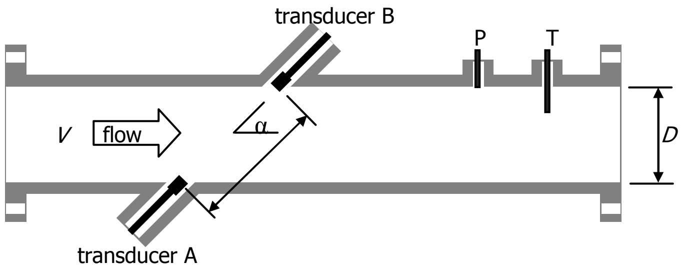

Figure 1 – Ultrasonic meter scheme and basic dimensions

Ultrasonic meters are velocity meters by nature. That is, they measure the gas velocity within the meter body. By knowing the velocity and the cross-sectional area, volume flow can be computed.

The fundamental of ultrasonic meter depends of precise known of the transit time of an ultrasonic pulse traveling with the flow from transducer A to transducer B (t_{AB}). When this measurement is completed, a new pulse is launched from transducer B to A, now against the flow, and this traveling time can be determined (t_{BA}). The transit time of the signal traveling downstream is less than the upstream signal time.

Once the traveling times are known, downstream and upstream signal velocities, (v_{AB} and v_{BA}, respectively) can be determined by Eqs. (1-2).

$$v_{AB} = \frac{L}{t_{AB}} = c + V\, cos\, \alpha \tag{1}$$

$$v_{BA} = \frac{L}{t_{BA}} = c - V\, cos\, \alpha \tag{2}$$

Where L, α, t_{AB} *and* t_{BA} are known; V is associated to flow velocity and c is the gas sound of speed - *SOS*. The algebraic system composed by Eqs. (1) and (2) of can be easily solved for the unknowns c and V, which gives:

$$V = \frac{D}{sin\, 2\alpha} \frac{t_{AB} - t_{BA}}{t_{AB} . t_{BA}} \tag{3}$$

$$c = \frac{D}{2\, sin\, \alpha} \frac{t_{AB} + t_{BA}}{t_{AB} . t_{BA}} \tag{4}$$

Through Eqs. (3) and (4) it is possible to measure a variable associated to flow velocity V, as well as the speed of sound of flowing gas. Unfortunately, determining the correct flow rate within the meter is a bit more difficult task. The velocity V shown in Eq. (3) refers to the velocity on acoustic path. The velocity needed for computing flow rate, also known as bulk mean velocity, is the average gas velocity across meter´s area. In the pipeline, gas velocity profiles are not always uniform and often it is submitted to some swirl and asymmetrical flow profile as well. This make computing the average velocity a bit more challenging and it is out of scope of the present text.

However, it is important to be noted that gas velocity calculation in Eq. (3) is independent of speed of sound calculated in Eq. (4) and to compute speed of sound, gas velocity is not required. This is true because the transit time measurements t_{AB} and t_{BA} are measured within a few milliseconds of each other, and gas composition does not change significantly during this time. Also, it should be noted the simplicity of Eqs. (3) and (4) which are only dependent of L, α, t_{AB} and t_{BA}.

On the other hand, the thermodynamic speed of sound c can be obtained by state equations like AGA report no. 10 (2003), which only depends on chemical composition, pressure and temperature flow. Pressure and temperature flow are constantly monitored by P and T sensors respectively, installed next to the measurement section, as indicated in Fig. 1. Gas composition is more stable and it is monthly provided by oil platforms crew.

Such observation lead to conclude that comparison between measured and estimated speed of sound may be a way to check if transit times have been well measured and the flow velocity, by consequence since it uses the same parameters for its evaluation. Such self diagnoses procedure is especially attractive for measurement systems located on restricted access areas, like off-shore platforms.

This idea is not original at all and it was partially explored by some authors like Sakariassen (1997), Letton *et al.* (1998), Lansing (2000), Calander and Delsing (2000), Yeh *et al.* (2001) and Norli *et al.* (2005).

Now, aiming to evaluate a software able to compare SOS, after characterize gas flow composition, operational levels of pressure and temperature, it is proposed here a fast way to estimate thermodynamic sound velocity.

3. FLARE GAS CHARACTERIZATION

In order to characterize the gas flowing in flare lines, Tab. 1 show chromatographies from distinct off-shore platforms operating on Brazilian coast.

Table 1 – Gas cromatografies from off-shore platforms operating on Brazilian coast

	Platform A	Platform B	Platform C	Platform D	Platform E	Platform F
Gas constant R	8314,3	8314,3	8314,3	8314,3	8314,3	8314,3
Molecular weight M	19,12	20,74	22,09	22,37	22,79	29,47
Adiabatic constant k	1,2754	1,2552	1,2338	1,2505	1,2464	1,1929
Methane	89,44	84,59	75,90	72,82	70,82	62,88
Etane	5,10	6,12	10,79	12,96	14,57	9,78
Propane	1,67	4,47	7,24	8,72	9,31	10,72
i-butane	0,73	0,81	1,27	1,18	1,09	2,45
n-butane	0,79	1,64	2,06	1,98	1,91	5,72
i-pentane	0,40	0,41	0,43	0,33	0,28	1,66
n-pentane	0,30	0,53	0,48	0,36	0,32	2,21
n-hexane	0,35	0,39	0,26	0,19	0,14	1,74
n-heptane	0,30	0,33	0,15	0,00	0,11	1,43
n-octane	0,15	0,19	0,00	0,00	0,01	0,66
n-nonane	0,07	0,13	0,01	0,00	0,03	0,21
n-decane	0,02	0,07	0,00	0,00	0,02	0,03
C11	0,00	0,00	0,00	0,00	0,00	0,00
C12	0,00	0,00	0,00	0,00	0,00	0,00
Nitrogen	0,52	0,17	0,80	1,18	0,95	0,27
Carbon dioxide	0,16	0,15	0,61	0,28	0,44	0,24
Helium	0,00	0,00	0,00	0,00	0,00	0,00
Oxigen	0,00	0,00	0,00	0,00	0,00	0,00

Data from Tab. 1 is provided for standard state (T=20^{o}C, P=1 barA). An important point to be noted in Tab.1 is decreasing methane concentration from platform A to F.

Operational data from flare platforms are shown in Fig. 2 (gas pressure) and Fig. 3 (gas temperature).

From Fig. 2, pressure in flare pipelines varies from 0.97 to 1.12 barA and as can be seen in Fig. 3, gas temperature is found in a range from 13 to 37^{o}C, but most of them is around 25^{o}C. By observation of Figs. 2 and 3, it is reasonable to consider a typical flare pressure as 1 barA and a typical flare temperature as 25 ^{o}C, generally speaking.

4. PROPERTIES ESTIMATION OF FLARE GAS

The thermodynamic properties behavior of such gas mixture may be predicted by a state equation like AGA-10. Such simulations are shown in Figs. 4-8 for platform A data, as exemplification. Pressure range was made to vary from 0.5 to 10 barA and temperature range from 0 to 50^{o}C. All simulations using AGA-10 were performed by means of software FLOWSOLV^{TM} (2009), after previous validation of results and considering gas composition from Tab.1 and operational data from Fig.1,2.

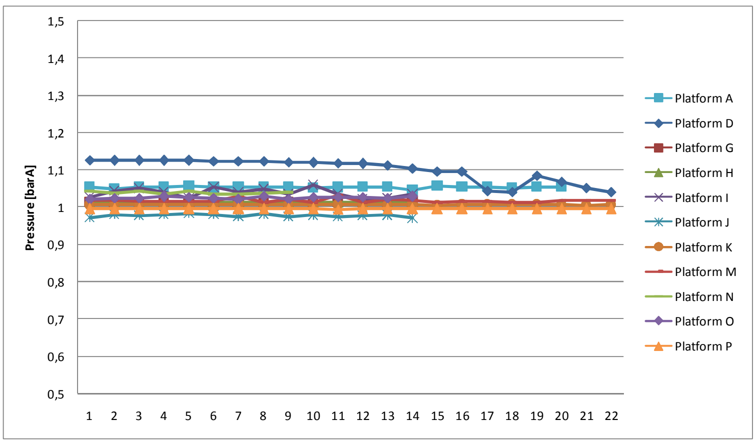

Figure 2 – Readings of gas pressure in flare tube [barA]

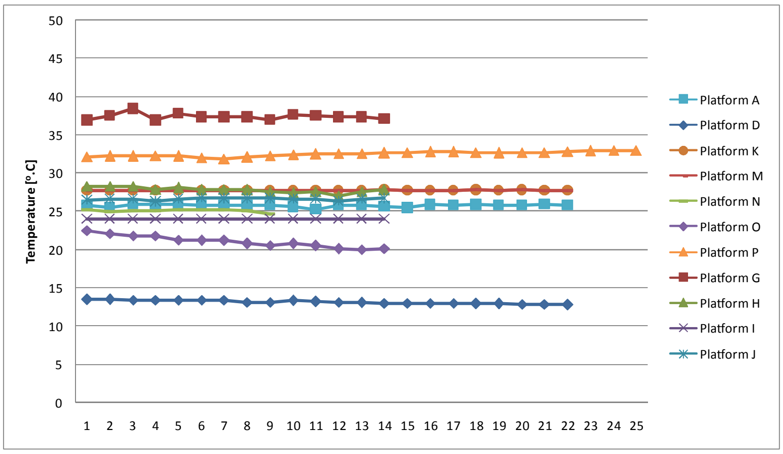

Figure 3 – Readings of gas temperature in flare tube [^{o}C]

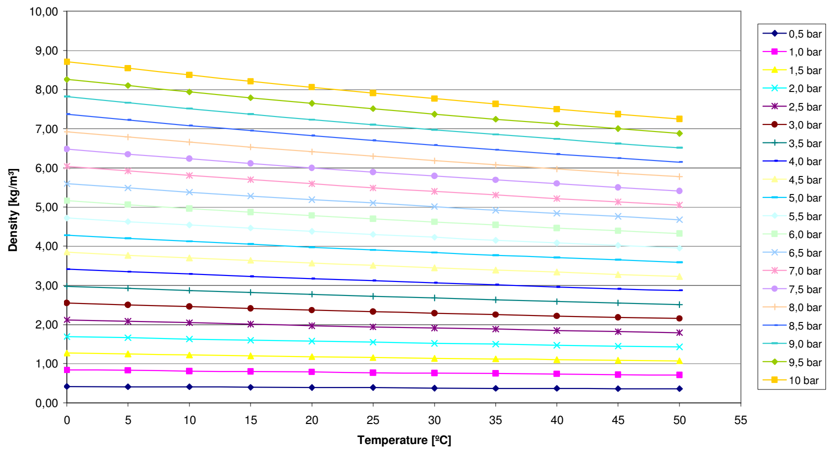

Figure 4 – Simulation of density for gas chromatography from platform A

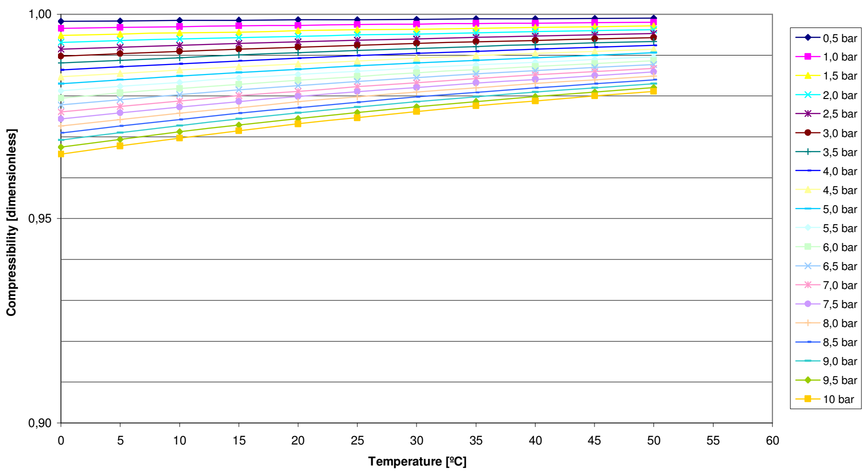

Figure 5 – Simulation of compressibility factor Z for gas chromatography from platform A

As expected, lower densities are simulated for lower pressures and higher temperatures as shown in Fig. 4. From Fig. 5, lower pressures and higher temperatures lead to a compressibility factor Z (dimensionless) tending to 1. At T=25^{o}C and P=1barA, simulation gives Z=0.9975, which means a behavior very closed to perfect gas approach.

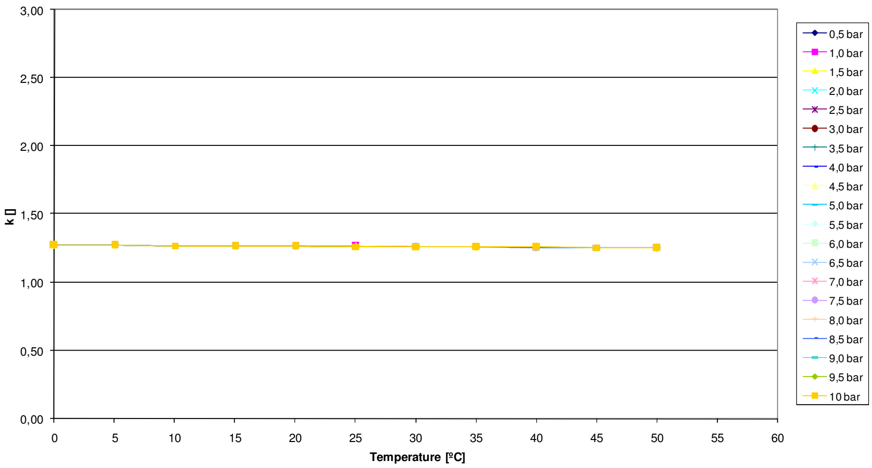

Figure 6 – Simulation of isentropic factor k for gas chromatography from platform A

The trend of isentropic factor $k=cp/cv$ kept almost uniform value, k=1.27, for all temperature and pressure simulated range, as demonstrated in Fig. 6. This value is much closed to the chromatographic data from platform A in Tab. 1 where k=1,275.

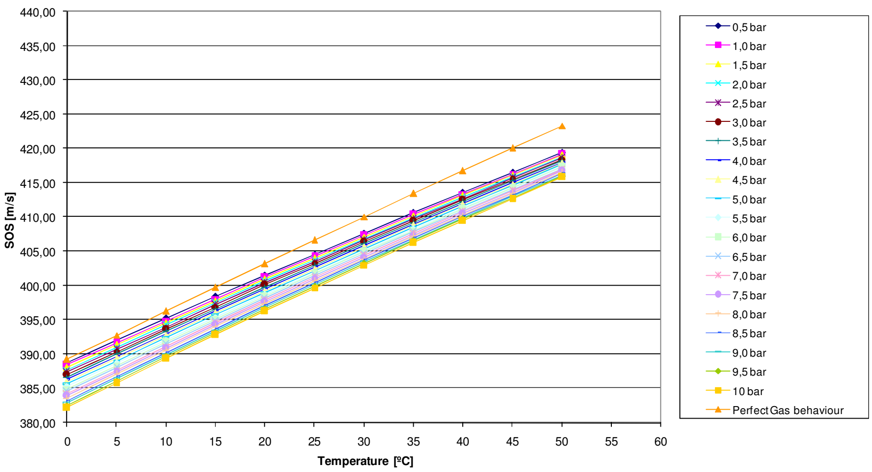

Figure 7 – Simulation of speed of sound - SOS for gas chromatography from platform A and perfect gas approach

Figure 7 shows the behavior of speed of sound: those simulated by AGA-10 and considering complete gas composition at different pressures and other considering perfect gas behavior which is given by classical formula Eq. (5), which is independent of pressure.

$$c_{perfect\,gas} = \sqrt{kRT} \tag{5}$$

In Eq. (5), c is the speed of sound SOS in m/s, k is dimensionless, R unit is kJ/kg.K and T may be given in Kelvin. It should be observed that AGA-10 and perfect gas present almost the same behavior, increasing with temperature and some influence of pressure variation, but lower pressure leads to a behavior more closed to perfect gas.

The differences of speed of sound obtained by AGA-10 and perfect gas simulations are distinguished in Fig. 8 for gas from platform A where can be see a maximum difference of 1.8% at T=0^{o}C and P=10barA. At T=25^{o}C and P=1barA, such difference keeps around 0.58%. Such differences are calculated as describe by Eq. (6):

$$dif = \frac{c_{perfect\,gas}(T) - c_{AGA\text{-}10}(P,T)}{c_{AGA\text{-}10}(P,T)} x100\% \tag{6}$$

Figure 9 shows the differences for gas from platform F with presents lowest methane concentration and so, surpassing perfect gas behavior, as can be noticed by differences levels reaching 6% at low temperatures. But at T=25°C and P=1barA, such difference still remains at 1,05%.

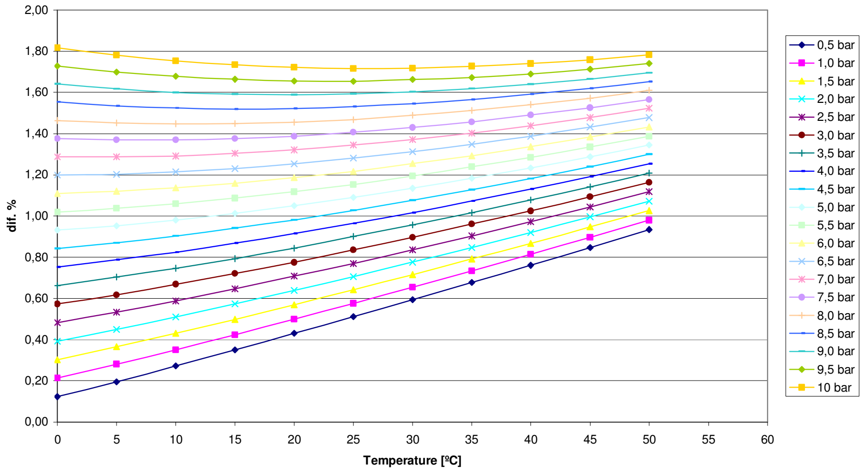

Figure 8 – Differences of speed of sound - SOS data obtained from AGA-10 simulation and considering perfect gas approach for gas chromatography from platform A.

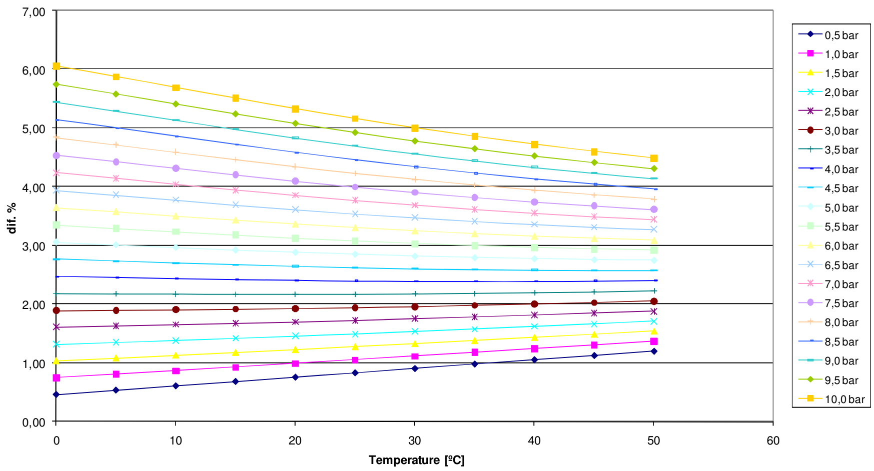

Figure 9 – Differences of speed of sound - SOS data obtained from AGA-10 simulation and considering perfect gas approach for gas chromatography from platform F.

The behavior described using Figs. 4-8 are similar for all chromatographies, but for a matter of synthesis, it is not shown here. Table 2 shows the differences at T=25°C and P=1 barA and the maximum differences for gas from of platforms A to F. It is included the speed of sound difference of pure methane compared to perfect gas approach, as well. It should be observed that the differences at typical operational state is less than 2%, and the maximum difference is around 6% at 10barA, which is far from a typical operational condition for flares tubes as can be inferred from Fig. 2.

Such results, obtained from distinct sources at distinct gas compositions and operational conditions, leads to confirm that is possible to build software considering perfect gas modeling in order to predict speed of sound in flare lines. It should be observed that, in this case specifically, absolute value of speed of sound is not as significant as the behavior of relative differences, which are similar for a large range of operational conditions. Of course, such approach may not offer the more precise simulation, but certainly, it is faster for computational purposes than computations evaluated using AGA-10 equation.

Generically speaking, the differences in simulations tends to be lower as higher is the methane concentration, which is predictable since methane is the natural gas component presenting lowest critical point, so closer to perfect gas behavior at T=25°C and P=1 barA than other gas concentrations.

Table 2 – Speed of sound differences between AGA-10 calculations and perfect gas approach for two thermodynamic states: typical operational condition and extreme pressure.

Platform	Difference [%] at 25°C and 1 barA	Maximum differences [%] at 10 barA
pure methane	0,09	0,87
A	0,58	1,82
B	0,59	2,26
C	0,10	2,21
D	0,89	3,11
E	0,87	3,22
F	1,05	6,05

In order to compare SOS simulations and readings, Fig. 10 show some plots for available data for platform A, measured direct by flare ultrasonic flow meter constituted by single acoustic path.

From Fig. 10, it is observed that differences between simulations keep less than 1% while differences between simulations and readings reach averaged values around 13%. It is important to notice that such differences are very stable, presenting averaged standard deviation around 0,22%. Such behavior and respective difference levels are observed for all operational readings available at different platforms, which means the best SOS evaluation, performed by AGA-10, is very close to perfect gas approach considering flare flows, but both simulations presents a stable difference compared to SOS readings direct from flow measurement system.

Such behavior leads to conclude that, for long term readings it is possible to establish a typical difference between readings and perfect gas approach in order to propose the self-diagnoses software to check ultrasonic flow meter specific for flare metering operations.

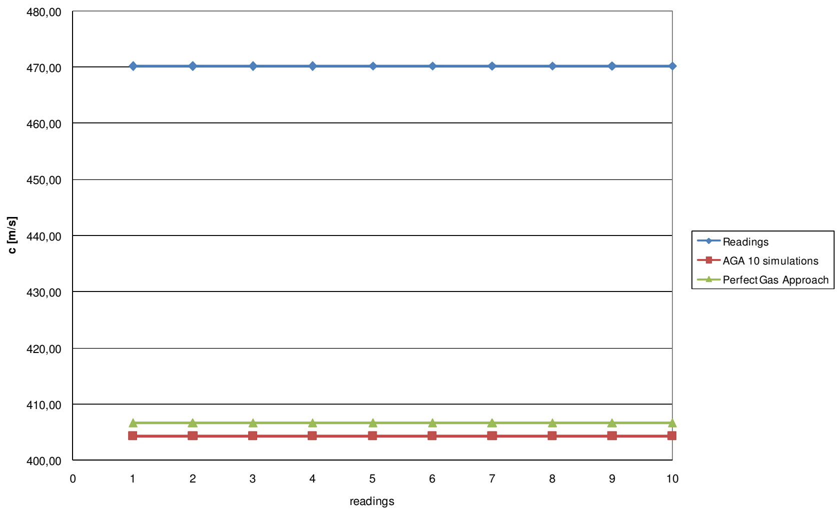

Figure 10 – Plots of operational readings of SOS measured at platform A compared with AGA-10 simulations and perfect gas approach.

Such software is based on the following logic: once the measured speed of sound c, obtained by Eq. (4), is checked against a simulated SOS, it can be said that pulses traveling times t_{AB} and t_{BA} are correct. But, as pointed out by Eq. (3), such pulses traveling times are used to calculate flow velocity v as well. So, it can be inferred that if the traveling times are correct, the flow meter health is satisfactory.

Present study still provides interesting theoretical perspectives about usage of atmospheric wind tunnels to calibrate ultrasonic flow meters for flare applications as well, as pointed out by Hill *et al.* (2002).

5. ACKNOWLEDGEMENTS

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