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ANALYSIS OF HIGH PRESSURE TESTS ON WET GAS FLOW METERING WITH A VENTURI METER

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Abstract

This work deals with the flow metering of wet gas issued from high pressure natural reservoirs. Some recent results obtained from tests performed on the CEESI facilities are presented. They are performed at 75 bars with 0.6 beta ratio Venturi meter installed in horizontal pipe configuration. Correction factors obtained are compared to predictions deduced from the flow modelling inside of the meter. These results are analysed in order to explain the agreements or disagreement obtained between the experiments and the flow modelling.

Introduction

On gas production fields from natural reservoir, the fluid flow rates must be accurately count for economical and technical point of view. As the gas present in a natural basin at variable pressures (up to 700 bar or more for high pressure layers) is brought up to surface (with a pressure of about 50 to 200 bar) to be treated and evacuated, condensation phenomena occur and a liquid phase appears, formed from condensates and water. In many cases the gas volume fraction (GVF) is higher than 95% (wet gas), and the flows encountered are of an annular dispersed type.

There are currently two types of approaches to carry out the metering of this wet gas. The first consists in separating the two phases and metering each separately. The second consists in metering the overall two phase flow with a dry gas flow meter for which correction law are established in order to take into account the influence of the liquid phase. This second method seems of growing interest nowadays. On the market, measuring devices based mainly on Venturi concept are proposed by different meters manufacturers. Generally, the presence of the liquid phase provokes an increase of the differential pressure between the upstream and the throat sections. In order to deduce the true gas mass flow rate flowing in the pipe, a "black box" type analysis based on empirical correlations is used. In parallel, a new approach based on a flow modelling of the two phase flow behaviour inside of the meter was proposed by Van Werven et al [1], Lupeau et al [2]. In order to valid these different methods in realistic flow conditions, high pressure tests are performed in different laboratories (NEL, CEESI, KLAB..).

The aim of this paper is to present some results obtained on the CEESI test facilities on a horizontal pipe configuration using a 0.6 beta ratio Venturi meter. The correction factors are compared to flow modelling results and empirical correlations published in the literature.

Test configuration.

The aim of these tests was to test the Venturi behaviour in controlled flow configuration. In particular, it was important to place the meter in a reference flow condition obtained with a sufficient upstream straight pipe length. For a two phase flow, Kataoka and Ishii defined the distance needs to obtain an equilibrium condition by the following expression:

$$Z/D = 440 \frac{We_l^{0.25}}{\text{Re}_f^{0.5}}$$

with $We_l = \frac{\rho_g j_g^2 D}{\sigma} \left(\frac{\Delta\rho}{\rho_g} \right)^{\frac{1}{3}}$

and $\text{Re}_f = \frac{\rho_f j_f D}{\mu_f}$

In these formulas, j_g and j_f correspond to the superficial velocities of the gas and liquid. They are defined by the ratio between the volume flow rate of the corresponding phase and the whole pipe area. In order to verify this expression the Venturi meter was placed 144 D downstream of a 90° bend. The venturi was designed according to the ISO recommendations. The pipe and the throat diameters are equal to 0.194 m and 0.1162 m respectively giving a β ratio equal to 0.6.

The test chart contains 65 points for which the Gas Volume Fraction (GVF) varied from 95%

to 100% and the Water Liquid Ratio (WLR) or the Water Cut from 0 to 100%. The range of the different parameters is indicated in table 1.

Test processing

A lot of investigations have been performed on the measurement of two-phase flows by means of ΔP flow meters (orifice plate, Venturi, V-Cone). The main approach is to define a correction factor depending on the flow characteristics to calculate the actual flow rate of gas and liquid in the pipe. This correction using empirical correlation is defined as follows:

For a given Venturi meter defined by its β ratio (= d/D), if ΔP_t is the actual differential pressure measured on the flow meter with a two-phase flow, then the total mass flow rate of the mixture will be:

$$Q_{mt} = C_D \frac{\pi d^2}{4} \varepsilon \frac{1}{\sqrt{1-\beta^4}} \sqrt{2\rho_t \Delta P_t} = K\sqrt{2\rho_t \Delta P_t}$$

Parameter	Range
j_g (m.s^{-1})	6 - 16
j_w (m.s^{-1})	0.25 – 0.75
j_o (m.s^{-1})	0.25 – 0.75
P (bar)	73 - 76
T (K)	304 - 306
ρ_g (kg.m^{-3})	58 - 61
ρ_w (kg.m^{-3})	998
ρ_o (kg.m^{-3})	737
μ_g (kg.m^{-1}.s^{-1})	1.36 10^{-6}
μ_w (kg.m^{-1}.s^{-1})	0.78 10^{-4}
μ_o (kg.m^{-1}.s^{-1})	1.61 10^{-3}
σ_w (N.m^{-1})	0.073
σ_o (N.m^{-1})	0.0105

Table 1: Flow parameters

In this expression ρ_t is the apparent density of the mixture. The discharge and the compressibility coefficients C_D and ε are given by standards.

If this density is replaced by the gas density, the apparent mass flow rate of gas Q_{mgs} will be:

$$Q_{mgs} = K\sqrt{2\rho_g \Delta P_t}$$

In fact the actual mass flow rate of gas Q_{mg} is:

$$Q_{mg} = K\sqrt{2\rho_g \Delta P_g}$$

Thus, a correction factor Φ_g can be introduced:

$$\Phi_g = \frac{Q_{mgs}}{Q_{mg}} = \sqrt{\frac{\Delta P_t}{\Delta P_g}} \quad \text{i.e } Q_{mg} = \frac{Q_{mgs}}{\Phi_g}$$

In this description, the K factor is supposed constant and its variations due to the liquid phase are taken into account in the Φ_g factor.

Flow modelling

In order to predict the correction factor, a flow modelling method described in Lupeau et al [1] is used. The flow is divided in two regions: the convergent and the throat. In each zone, integrated balance equations (mass and momentum conservation) are applied on three flow entities; the gas flow, the liquid film and the dispersed flow. In each pipe section, each flow entity is defined by its local velocity v and its flowing area S. In these equations, source terms are used to describe the momentum and mass exchanges. This concerns the momentum gas/liquid film interaction at the interface, the momentum exchange between the gas and droplets and the mass exchange between the film and the droplets due to the entrainment. The model supposes that no mass exchange between the liquid and the gas occurs in the meter (evaporation and condensation).

Furthermore, in the convergent zone, no mass transfer between the film and the droplets is considered. On the contrary, an atomization of the liquid film is taken into account at the convergent/throat junction.

The volume flow rate of liquid atomized is deduced from a correlation obtained by Salque et al [2]. This correlation is based on a Weber number computed from the local interfacial shear stress τ_i exerted by the gas on the liquid film and the wave amplitude as length variable. It was observed that the film atomization appears for Weber numbers higher than a critical value. In consequence the atomization rate is computed from the following expression:

$$f = \frac{Q_{atomized}}{Q_{film,0}} = 1.2 \cdot \Delta We_{\tau_i, \sqrt{\delta_b \cdot \delta_p}}$$

After some calculations, it can be expressed by:

$$We_{\tau_i, \sqrt{\delta_b \cdot \delta_p}} = \frac{\tau_i \cdot \sqrt{\delta_b \cdot \delta_p}}{\sigma} = We_{\tau_i} \frac{1}{A}$$

with

$$We_{\tau_i} = \frac{\sqrt{j_{film} \cdot D \cdot \mu_l \cdot \tau_i}}{\sigma}$$

The wave amplitude is characterised by $\sqrt{\delta_b \cdot \delta_p}$ where δ_b is the minimum film height between 2 peaks and δ_p the film height reached at the peak locations. The A coefficient was introduced by Pearce. It corresponds to the ratio between the wave amplitude and the mean film thickness.

$$A = \frac{\sqrt{\delta_b \cdot \delta_p}}{\overline{\delta}}$$

For water flow, A = 1.1 and for oil flow A=5.6. The interfacial shear stress is computed from the Wallis correlation.

$$\tau_i = \tau_{g,dry}\left(1 + 300\frac{\delta}{D}\right)$$

where $\tau_{g,dry}$ is the wall shear stress obtained in dry gas condition.

To define the size of the droplet atomized, an empirical correlation proposed by Azzopardi and Govan(3) is used.

$$d_{P\_throat} = \lambda_T\left(\frac{15,4}{We'^{0,58}} + 3,5\frac{\rho_g Q_{mp\_upstream}}{\rho_p Q_{mg}}\right)$$

where:

$$\lambda_T = \sqrt{\frac{\sigma}{\rho_p g}} \quad \text{and} \quad We' = \frac{\rho_p v_g^2 \lambda_T}{\sigma}$$

The initial droplet velocity $v_{p\_throat,0}$ is fixed by the average liquid film velocity at the end of the convergent.

The boundary conditions at the inlet of the convergent section concern the gas and droplet velocity, the liquid distribution between the droplets flow and the wall liquid film and the droplet size. The gas velocity is fixed by the gas volume flowrate and the gas area. No slip is considered between the droplets and the gas flow. The liquid distribution f corresponds to the ratio between the droplet flow rate and the total liquid flow rate. It is deduced from the Ishii correlation:

$$f = \tanh(7.25 \cdot 10^{-7} We^{1.25} \text{Re}_{l,1}^{0.25})$$

The droplet size is deduced from the Azzopardi and Govan correlation.

The balance equations are solved in the WEGMOVE[©1] code.

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[1] WEt Gas MOdelling of a Venturi meter

Correlation taken into account

The experimental results obtained during the tests were also compared to different correlations. The two first are the following well known "de Leeuw" and "Equivalent Density Correction (EDC)".

De Leeuw:

$$\Phi_g^2 = 1 + C \cdot X + X^2$$

$$\text{With}: C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$$

In this expression :

$n = 0.41$ for Froude number between 0.5 to 1.5

$n = 0.606 \cdot \left(1 - e^{-0.746 Fr_g}\right)$ for Froude number above 1.5

The Froude number is defined by :

$$Fr_g = \frac{j_g}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}}$$

Equivalent Density Correction (EDC):

This correlation is deduced from a model in which the velocity of the liquid phase is supposed to be equal to the gas velocity in each pipe section. This condition is encountered in the case of very small droplets in a gas phase. In this case, the n exponent appearing in the de Leeuw correlation is equal to 0.5.

Reader Harris:

The third correlation was proposed by Reader Harris and Graham [3]. The gas mass flow rate measurement with a Venturi meter depends on two parameters, the discharge coefficient C_D and the over-reading correction factor Φ_g.

The discharge coefficient is no longer deduced from dry gas tests but from the following expression:

$$C_D = 1 - 0.0463 \cdot \exp\left(-0.05 Fr_{g,th}\right)\min\left\{1, \sqrt{\frac{X}{0.016}}\right\}$$

where

$$Fr_{g,th} = \frac{Fr_g}{\beta^{2.5}}$$

The over-reading correction factor Φ_g is calculated with the same expression as de Leeuw except that the n exponent is now computed by the following expression:

$$n = \max\begin{Bmatrix} 0.583 - 0.18\beta^2 - 0.578\exp\left(\dfrac{-0.8Fr_g}{H}\right) \\ 0.392 - 0.18\beta^2 \end{Bmatrix}$$

where H depends on the liquid. It is equal to 1 for hydrocarbon liquid, 1.35 for water at ambient temperature and 0.79 for liquid water in a wet steam. It is a function of the surface tension of the liquid.

Modelling of the oil/water mixture

In the flow modelling and in the correlation, the liquid phase is considered as a unique fluid with its own physical parameters. In order to model the oil/water mixture, different authors have proposed considering the mixture as an equivalent fluid with given physical properties. They are dependant on the Water Liquid Ratio (also called Water Cut) λ_w which corresponds to the volume fraction of the water in the liquid phase:

$$\lambda_w = \frac{Q_w}{Q_w + Q_o}$$

If the definition of the equivalent density is quite obvious, the determination of the dynamic viscosity μ_l is more difficult. A first linear formula using the oil and water viscosities μ_o and μ_w can be used:

$$\mu_l = (1 - \lambda_w) \cdot \mu_o + \lambda_w \cdot \mu_w$$

For well mixed liquid, the correlation of Brinkman [4] is generally used:

$$\mu_l = \frac{\mu_{cont}}{(1 - \lambda_{dis})^{2.5}}$$

Here, λ_{dis} is the volume fraction of the dispersed liquid and μ_{cont} is the viscosity of the dominant liquid.

More recently, Pan [5] proposed an interpolation between the two previous formulas depending on a mixing degree coefficient C_m.

$$\mu_l = C_m \cdot \mu_{cont} \cdot (1 - \lambda_{dis})^{-2.5} + (1 - C_m) \cdot [(1 - \lambda_w) \cdot \mu_o + \lambda_w \cdot \mu_w]$$

with

$$C_m = 1 - \exp\left(\frac{-\mathrm{Re}_{3P}}{K}\right)$$

where Re_{3P} is a three phase Reynolds number defined by:

$$\mathrm{Re}_{3P} = \frac{\dot{m} \cdot D \cdot j_M}{j_g \cdot \mu_g + j_o \cdot \mu_o + j_w \cdot \mu_w}$$

$\dot{m}$ is the overall superficial mass flux (kg.m^{-2}.s^{-1}), and j_M is the overall superficial velocity.

$$j_M = j_g + j_o + j_w$$

From his experiments Pan fixed the K parameter to 15000.

The last parameter to be defined is the surface tension of the equivalent liquid. No correlation was found in the literature. Normally, the value of the dominant liquid is applied to the liquid mixture.

In order to determine the different properties, it is necessary to calculate the critical value of the Water Liquid Ratio corresponding to the inversion point $\lambda_{w,inv}$. Many authors consider that this phenomenon appears for a water cut equal to 0.5. Woods [7] used the correlation of Odozi [13] which link this critical value to the superficial velocity of the gas.

$$\lambda_{w,inv} = 0.3372 \cdot j_g^{0.2219}$$

Results obtained

Experimental data analysis

The correction factors obtained during the tests are plotted in figure 1. It is observed that the correction factor augments with liquid contents in the flow. Furthermore an influence of the Water Liquid Ratio is clearly obtained. In particular, it is seen that, when the water content augments in the liquid, the correction factor augments first, reach a maximum around 70% and then decrease. Such behaviour is due to an inversion phenomena observed previously by Pan [5], Wood *et al* [6], Açikgoz *et al* [7] for pipe flows and more recently by Cazin et al [8] and Gajan *et al* [9] for Venturi flow meters. Pan notes that this inversion phenomenon is linked to a modification of the liquid fluid in contact with the wall. Gajan et al noticed that this inversion phenomenon modify the atomisation rate of the liquid at the end of the convergent.

By using the Odozi correlation, the inversion phenomenon corresponds to WLR between 50% and 63 % which is lower than the value obtained during the tests.
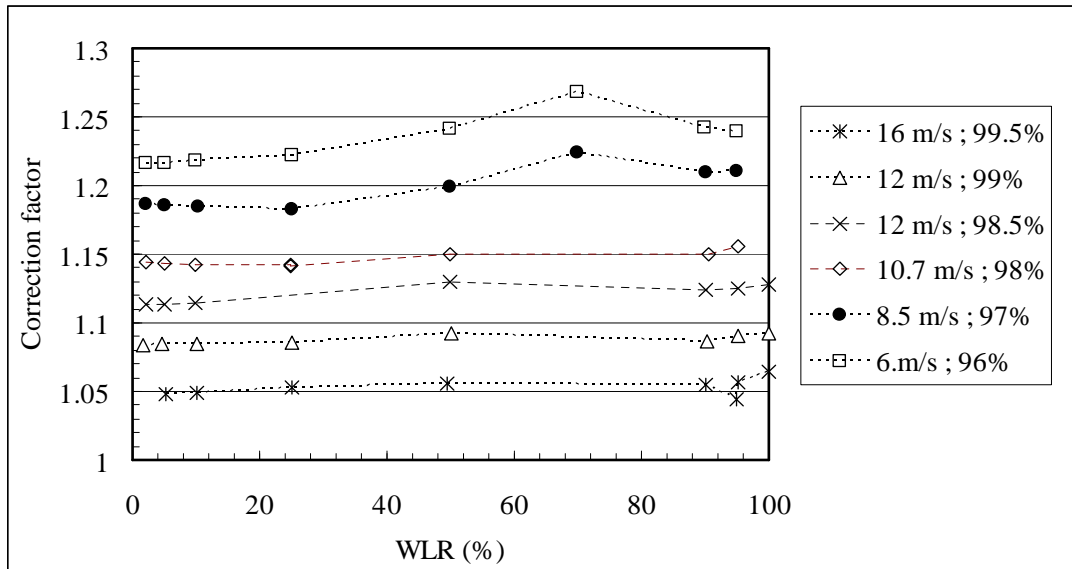
Figure 1: Influence of the WLR and the GVF on the correction factors
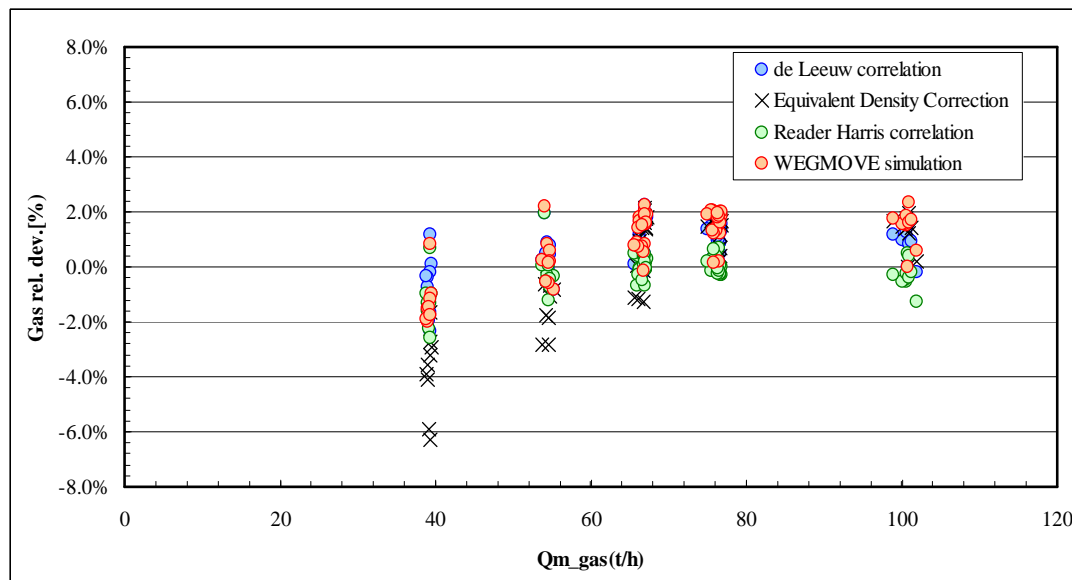

Figure 2: Deviation in the correction factor of the predictions obtained by the flow modelling and correlations with respect to the experimental results.

Comparison of these data with the flow modelling results and the predictions given by the three correlations detailed previously is plotted in figure 2. It can be noticed that, except the equivalent density correction, deviations between experiments and predictions are within ±2%.

Furthermore the flow modelling permits to describe the flow phenomena inside of the Venturi meter. In a first step, the inlet boundary conditions in terms of film thickness and droplet sizes are calculated. An example is given in figure 3 for a GVF values equal to 97%. The modification of the water content in the liquid phase modifies the liquid distribution in the pipe and the droplet size. For WLR value

around 70%, the increase of the droplet size and the film thickness induced a diminution of the correction factor predicted by WEGMOVE.

The influence of these boundary conditions on the flow predicted inside of the meter is observed in figure 4 for two WLR values around the inversion zone predicted by the Odozi formula. Inside of the convergent and the throat sections, the droplets are accelerated. The difference between the droplet velocity and the gaz velocity is due to the inertia of the droplet. It is called the "slip velocity". Smaller are the droplets, lower is the slip velocity. At the same time in the convergent section, the shearing effect on the wall liquid film augments inducing a decrease of its thickness. At the end of this

section, the atomisation process induces a rapid decrease of this thickness which is then considered constant in the throat section. The new droplets issued from this atomisation process are then accelerated. Their initial velocities correspond to the film velocity at the end of the convergent section.

Before the inversion phenomena, the WEGMOVE code predicts that no film exits and the liquid flow upstream of the meter is formed by only droplets of small size (100µm) inside of the meter. Due to their small inertia, the slip velocity is low.

For the other flow condition, the Ishii expression predicts that a part of the liquid

flows as film on the wall pipe. From the fluid properties and the flow conditions, its thickness is evaluated to 125 µm. In the convergent section this thickness diminishes and reaches 62 µm at the end of this section. At the inlet of the throat section, around 6% of the film flow rate is atomised and the liquid film thickness is reduced to 50 µm. The droplets size issued from this atomisation process is equal to 135 µm, so they are greatly accelerated. In parallel, the initial droplets size is equal to 450 µm. In consequence, their slip velocity remains important even in the throat section.
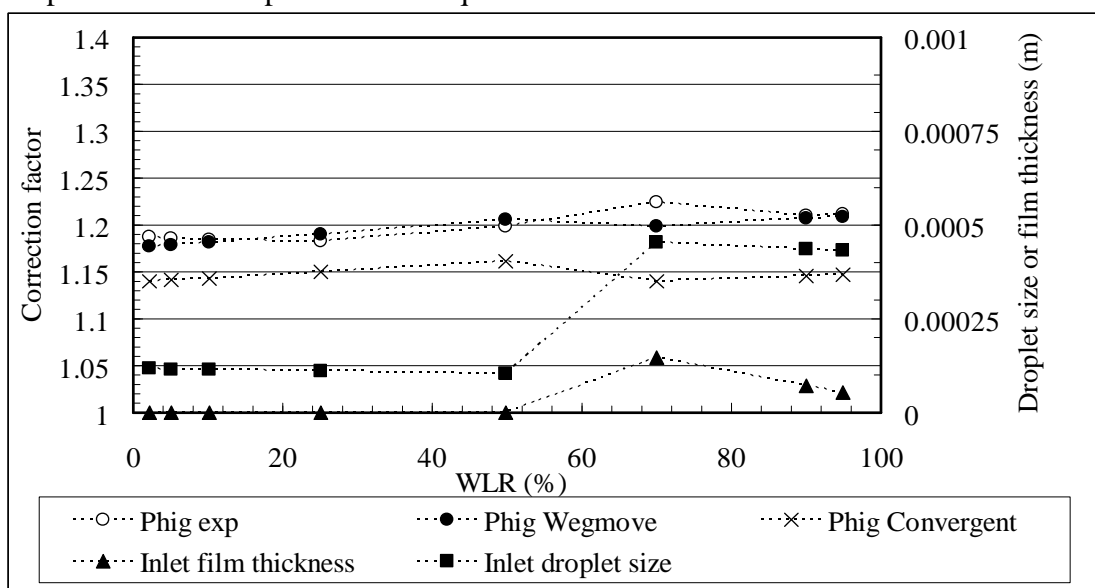

Figure 3: Inlet boundary conditions determined from WEGMOVE code
(GVF = 97% ; 0 < WLR < 100 %)

Conclusions

This paper presents an analysis of high pressure tests performed on a Venturi meter submitted to a wet gas containing water and oil in the liquid phase. The test procedure was defined in order to analyse the influence of the GVF and the WLR on the correction factor. Furthermore, in order to facilitate the validation of a flow model, the installation of the meter was defined to obtain a steady flow at its inlet. The correction factors deduced from these tests are compared to available correlations of the literature. Furthermore, they are used to validate the flow model developed in a first step from low pressure experiment.

The analysis of these results confirms the influence of the inversion phenomena on the

Venturi behaviour. Nevertheless, it seems that the inversion point predicted by the Odozi formula does not correspond to the value obtained during the tests.

Furthermore, the comparison with the main correlations of the literature and with the flow model gives satisfactory results and the accuracy obtained during these tests remains around 2%.

Nevertheless, in most of the industrial application, the measurement device is placed to a flow disturber like a blind Tee. Previous analyses of tests performed in such configurations, show that the accuracy of the methods are degraded reaching in some cases 8%. In order to improve these results, it is necessary to take into account the influence of these inlet boundary conditions. This can be

easily done by the modelling approach. Nevertheless, it is necessary to modify the correlation used in the model. To do so, specific tests using up to date measurement techniques had be realized. Such an attempt will be perform in the near future.

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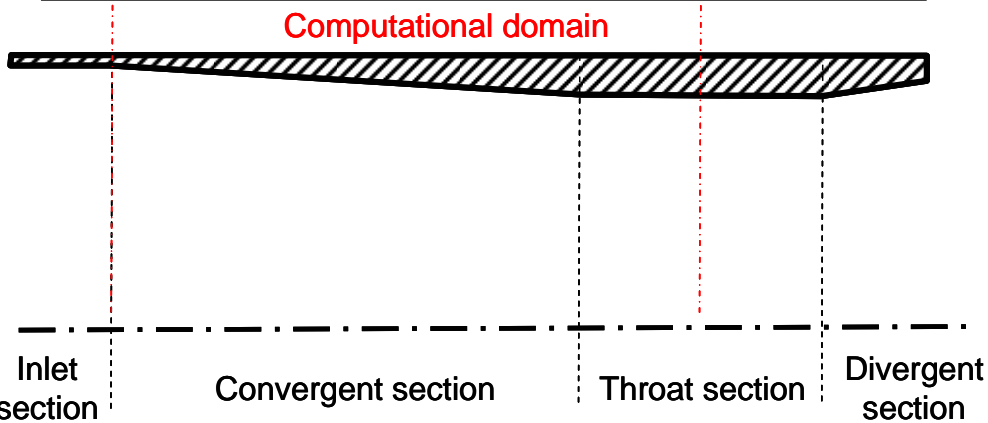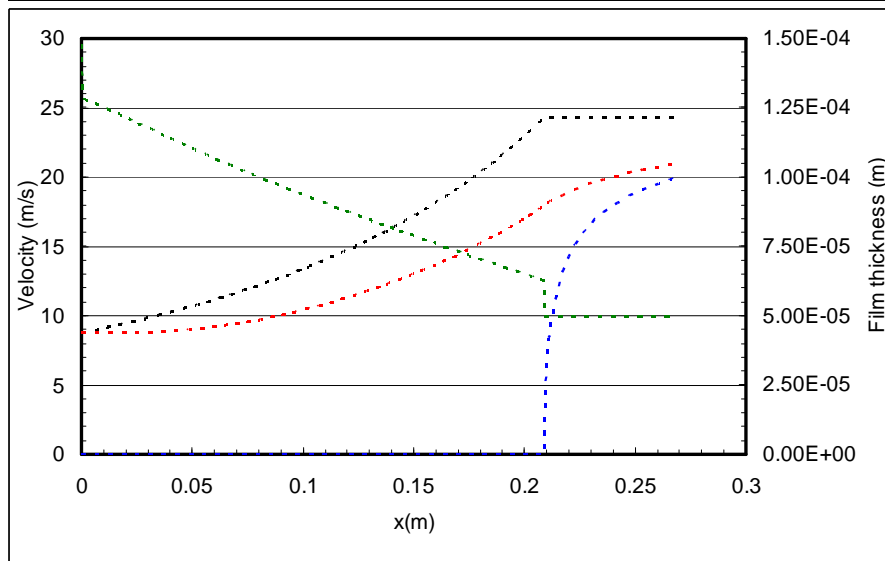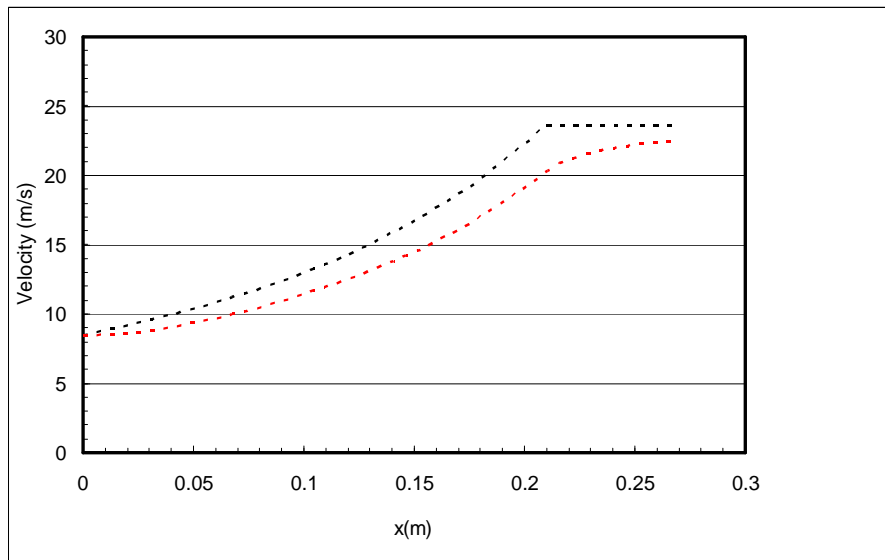
Figure 4: Distribution of the different parameters inside of the Venturi meter for two WLR
Upper graph: WLR = 50% ; Lower graph: WLR =70%
(GVF = 97% ; j_g = 8.6 m/s ; j_l = 0.26 m/s ;WLR = 70%)