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Transient Phenomena in Liquid/Gas Flow in Pipelines

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Abstract – Mass continuity and the equation of motion govern the flow of a fluid in a pipeline. Such flows are also affected by the elasticity of the pipe however. The effect of elasticity of the pipe can be taken into consideration by assuming it to be linear with constant mechanical properties. However, often the elasticity property of the pipe is neglected in the case of gas flow. To study transitions in liquids in liquids, furthermore, this property is integrated and added to the geometrical characteristics of the pipe wall in the expression of the velocity of sound. In this study we apply the method of characteristics to investigate the transient phenomena in a two-phase homogeneous flow. The analysis is based on models that take into account both the geometrical parameters of the pipe, such as the elasticity of the walls as well as the physical parameters such as the flow quality, namely the mass fraction of the gas in the two-phase mixture flow.

***Keywords*:** Transitions, MOC, Pressure Wave, Homogeneous Fluid.

1. Introduction

Studies of the transient flows often focus on a single-phase fluid such as highly compressible gases, or, pure incompressible liquids, as those classified in the category of water hammer phenomenon. Moreover, if the elasticity of the pipe is taken into consideration, it is assumed to be linear with constant mechanical properties. Unfortunately, often the elasticity property of the pipe is neglected in the case of a gas flow, whereas, to study transitions in liquids this property is integrated and added to the geometrical characteristics of the pipe wall in the expression of the sound velocity. However, for pipes that exhibit significant viscoelastic effects (for example, plastics such as PVC and polyethylene), it was showed that these effects can influence the wave speed in pipes and must be accounted for if highly accurate results are desired.

Generally, in industrial fluids including mixed fluids of different phases, the presence of even a small amount of free gas significantly reduces the wave velocity below the value it would have had if the fluid was in a pure liquid state only. Therefore, if the mixture of fluids is treated as a pseudo-fluid, the propagation of the pressure wave is quite slow and we cannot detect real changes of the fast flow regime if the analysis is limited to flow velocities effectuate below the real speed of sound in the liquid. Chaudry et al. (1987) proposed to consider the gas / liquid mixture as a pseudo-fluid in the case where the void fraction is low. Studies conducted by Henry (1969) and Van Wijngaarden (1968) are good references which have generated significant results on the acoustic velocity in the bubbly flow. Hadj-taieb and Lili (1998) used mathematical models to study transitions in a two-phase homogeneous medium. The density ρ and the sound velocity were assumed to be pressure dependent, and the flow quality was assumed to remain constant. This latter condition is not always valid however. Mori et al., (1975) have conducted a study in which the void fraction is assumed to depend on the pressure rise in a two-phase flow. Padmanabhan (1976) states that the average void fraction varies necessarily in the case where a pressure gradient exists in a long pipe.

In this work, we apply the method of characteristics to investigate the transient phenomena in a two-phase homogeneous flow. The analysis is based on models that take into account both the geometrical parameters of the pipe like the elasticity of the walls, and physical parameters such as the flow quality (i.e., the gaseous mass fraction of the flow mixture, denoted as θ).

2. Physical Model

The mixture is made of a liquid carrying uniform size bubbles of gas, and is assumed to be polytropic. The equations of continuity and momentum that are commonly used are:

$$\frac{\partial(\rho S)}{\partial t}+\frac{\partial(\rho S u)}{\partial x}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial x}=-\frac{\lambda}{2d}u|u| \tag{2}$$

The study consists of two parts. The first rigid can be referred to as a rigid model in which the wall elasticity and the compressibility of the liquid are neglected. The second part of the study represents a quasi-rigid model in which the elasticity of the wall and the compressibility of the liquid are included. In both cases, the numerical simulation tests are performed on pipes of length L = 35.7m with a diameter d = 0.0196m. The friction effect is represented in terms of the Darcy-Weisbach constant λ.

3. Results

3. 1. Results for the Rigid Nodel Case

In the rigid model wherein the elasticity of the wall is assumed to have no effect and the compressibility of the liquid in comparison with that of the gas is neglected. The cross sectional area of the pipe is constant and equal to S_0. The density of the homogenous mixture can be represented as:

$$\rho(p)=\left(\frac{\theta}{\rho_g}\left(\frac{p_a}{p}\right)^{\frac{1}{n}}+\frac{(1-\theta)}{\rho_l}\right)^{-1} \tag{3}$$

Note that the gas in the bubbles undergo a polytropic process due to the effect of friction which gives the following relationship: $\left(\frac{p^n}{\rho_g^n}=\frac{p_0^n}{\rho_{g_0}^n}=cte\right)$

The celerity of the sound which is plotted on the Figure 1 can be represented by the following expression:

$$a(p)=\left(\frac{\theta n p_a}{\rho_g}\right)^{1/2}\left(\frac{p}{p_a}\right)^{(n-1)/(2n)}\left(1+\left(\frac{p_a}{p}\right)^{\frac{1}{n}}\frac{(1-\theta)\rho_g}{\theta\rho_l}\right) \tag{4}$$

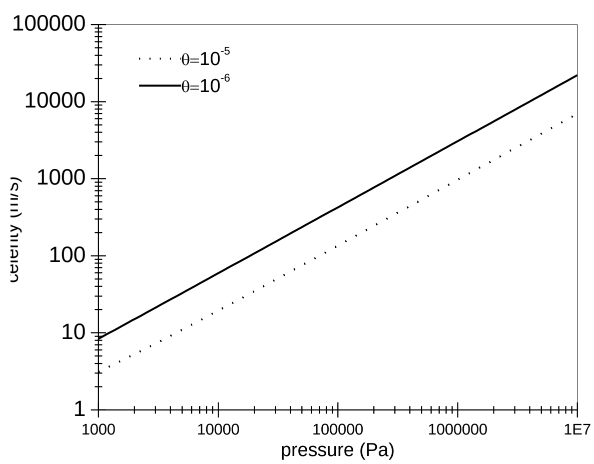
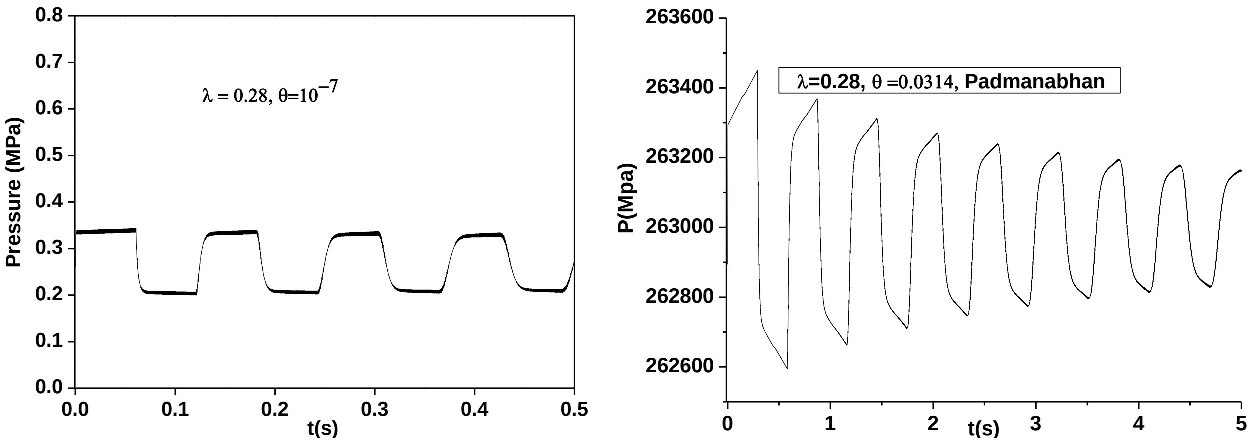


Fig.1. Variation of the sound velocity a(m/s) as a function of the pressure p(Pa).



a) Present study with MOC b) Experimental results of Padmanabhan

Fig. 2. Evolution of the pressure.

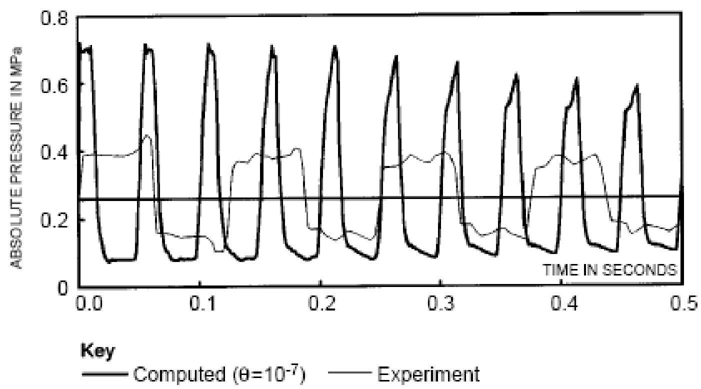


Fig. 3. Results of Hadj-Taeb- Experimental and – Newton-Raphson iterative Technique.

The comparison between the results obtained from a study based on the current MOC method, shown in Figure 2-a, and the numerical and experimental results of Hadj-Taieb and Lili (1998) given in Figure 3, leads to the following observations.

C1-Amplitude:

- In Figure 3, the amplitude of the pressure wave obtained by Hadj-Taieb and Lili (1998) based on a rigid model by numerical simulation using the Newton-Raphson iterative technique is around 0.7 MPa.
- In experimental results the amplitude is less than 0.4 MPa as shown on the Figure 3.
- Results obtained in the present investigation (MOC) depicted in Figure 2-a, shows an amplitude which is around 0.37MPa.
- C2- Number of periods in 0.5s:
- Figure 3, we note from the numerical results of Hadj-Taieb and Lili (1998), that there are 10 periods.
- In the experimental results which are displayed in Figure 3, there are only four periods.
- Our work, consistent with the experimental results, predicts that there are only four periods as shown in Figure 2-a.

From the aforementioned observations C1 and C2 we can conclude that the results obtained with the method of characteristics are closer to the experimental data and therefore better reflects reality than the digital model of Hadj-Taieb and Lili (1998). Moreover, the authors have concluded that the rigid model which is proposed to simulate a two-phase flow is not valid when the flow quality θ is low because the predicted speed of sound becomes excessively high. This leads us to conclude that the predicted pressure amplitudes are too high and therefore are unphysical meaning. This is in contradiction with the classical concept of water hammer.

3. 2. Results for the Quasi-rigid Model

In the quasi-rigid model case, the liquid compressibility and the pipe's elasticity are considered to be too large to be neglected. In addition, the cross-section S, the density ρ and the speed of sound 'a' all dependent on pressure as can be seen in Figures 4 and 5. Usually, the pipe's elasticity is deduced from the following equation:

$$\frac{dS}{S\sqrt{S}} = \frac{2c}{Ee\sqrt{\pi}} dp \tag{5}$$

In which E is Young's modulus, c is the pipe constraint factor, and e is the wall thickness.
It is similar to the expression that is given by van Wijngaardan (1972).
After integration, we find the following expression for the cross-section S as a function of pressure p and thereby the density of the mixture:

$$\rho = \left(\frac{\theta}{\rho_g} \left(\frac{p_a}{p} \right)^{\frac{1}{n}} + \frac{(1-\theta)}{\rho_l} \exp\left({(p_a - p)}/{K_l} \right) \right)^{-1} \tag{6}$$

K_l is the compressibility of the liquid

As an application, we will use the model which has already been tested by Hadj-Taieb and Lili (1998) as a reference for a validation of our simulation. Validation will be done on the classical concept of water hammer.

The physical problem is defined as follows conditions: u is the fluid velocity, L=35.7m, d=0.0196m, E=0.9 10^{11} Pa, e = 0.001m, c = 0.9, P_a= 0.263 MPa (Initial pressure), λ: represent the friction coefficient and Q_0 =0.000031m^3/s, the inlet mean velocity is found from u_e (x=0)= 4 Q_0 /(Π d^2) , $\theta=M_g/(M_g+M_l)=0$ (i.e., the fluid is pure liquid free of gas), ρ_l= 1000kg/m^3, and ρ_g= 1.29kg/m^3.

Figure 6 shows a validation of the quasi-rigid model tested on the water hammer effect. When the fluid is clean with no gaseous contamination (θ = 0), the evolution of the pressure wave obtained by the method of characteristics is much close to results obtained experimentally than that obtained by the finite difference simulation scheme of Lax and Wendroff (1960).

In conclusion, we can deduce that the simulation of two-phase flow for the cases of rigid and quasi-rigid models with the method of characteristic gives better results than those given by the finite difference scheme of Lax Wendroff as presented by Hadj-Taieb and Lili (1998).

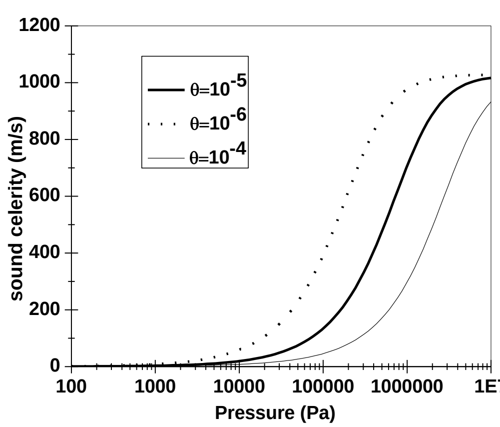


Fig. 4. Variation of the sound velocity with the pressure. Influence of the fluid quality, θ.

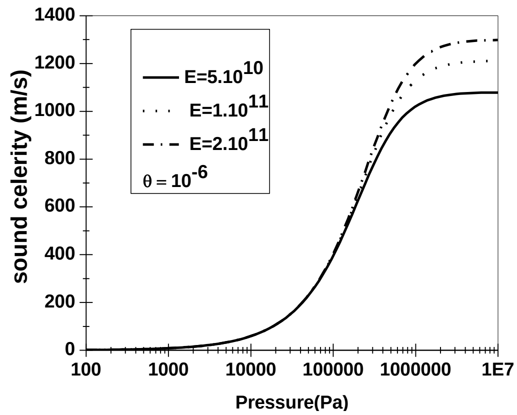


Fig. 5. Variation of the sound velocity with the pressure. Influence of Young modulus, E.

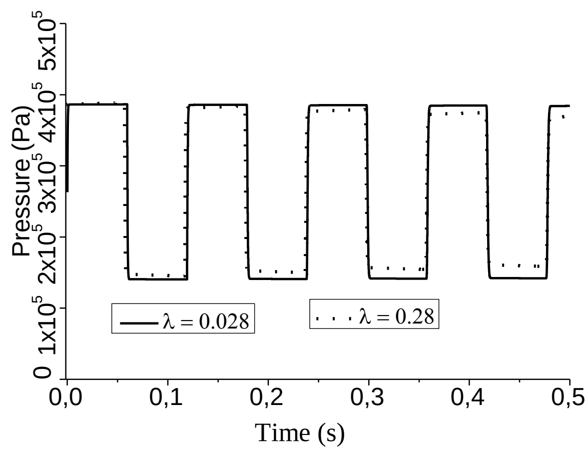


Fig. 6. Validation of the quasi-rigid model tested on the water hammer case.

Remark: If $E \approx \infty$ then $S=S_0$ = const., and if $K_l \approx \infty$, then the liquid compressibility vanishes and the equation for the density of the liquid becomes independent of the pressure. The model therefore resembles the case of a rigid model.

4. Impact of the Physical Parameters u_e, p_e and θ

Often it is assumed that the presence of a small amount of gas in the fluid leads to the conclusion that the pipe is inelastic and the wall is thick enough, and consequently the rigid model is certainly valid. Streeter and Wylie (1982) have confirmed this idea. However it is not always easy to deal with this issue and the validity of this observation depends among others on the flow quality.

To better understand this issue, we focus on the conservation equations and in particular the continuity equation.

The continuity equation in the steady state is given by the relationship below:

$$u\rho_x + \rho u_x = 0 \qquad (7)$$

Hence

$$\rho u = cte = \rho_e u_e \qquad (8)$$

We assume that the conditions at the entrance of the pipe are as follows:
$p(x=0) = p_e = 263000$Pa, $u(x=0) = u_e = 0.1027$m/s and $\rho_e = \rho(p=Pa)$.

The conditions mentioned above have a crucial role in the stability of the mass balance in the pipeline. Whalley (1996) suggested that the homogeneous model can be reliable and give good results if the mass flow satisfies the following condition, $G = \rho u > 2000$ kg/(m^2.s).

Padmanabhan (1976) stated that apart from the simplicity offered by the homogenous model equation in its implementation, this model is not the most widely recommended technique for simulating two-phase flows. For this, the following steps will be devoted to defining the most appropriate physical conditions for best results with the homogeneous model.

We ask the following questions: What are the physical conditions that are favorable to the application of the homogeneous flow model in the presence of a wave which propagates in the flow?- Also, what are the distinctions between homogeneous and non-homogeneous models?

Martin et al., (1976) and also Martin and Padmanabhan (1979) assumed that the peak pressure in a two-phase flow of a fluid which has a large void fraction, as for example in the slug flow regime, can be easily solved by a homogeneous model with the method of characteristics.

The applications of the conditions of Hadj Taieb and Lili (1998) in the case of an homogeneous flow (θ_{max} = 0.0314) as presented in the study of Padmanabhan (1976), leads to the results that are shown in Figures 7 and 8. At θ_{max} = 0.0314, corresponding to the homogeneous case treated by Padmanabhan (1976), the density in the Figure 7 appears to be approximately constant and very low, equal to 39.51kg/m^3. In contrast, at $\theta_{min} = 10^{-7}$, the density is maximum and equal to about 1000kg/m^3. Similarly, we note obviously the non-linear profile of the density in the range of pressures considered (around of 0.5MPa).

In the model of Hadj-Taieb and Lili (1998) where the initial conditions are defined by p (x = 0) = p_e = 263000Pa and u (x = 0) = u_e = 0.1027m / s, we see that for several values of θ, the homogeneous density may not exceed ρ_{max} = 1000kg/m^3 which corresponds to the liquid case.

Changes in the density and the velocity as a function of the pressure which are shown in Figures 7 and 8, confirms that the rigid model for two-phase flow, in which the liquid phase is incompressible, presents a mass flow less than the minimum required for the applicability of homogenous flow assumption, namely 2000kg / (m^2.s). For this reason the model of Hadj-Taieb and Lili (1998) is not perfectly suited for the simulation of this homogeneous flow case. This is because the mass flux at the entrance is, $G = \rho u$ = 102.5 kg/ (m^{2}s), which is considerably lower that the aforementioned lower limit of mass flux 2000 kg/(m^{2}s) for the suitability of homogeneous flow model.

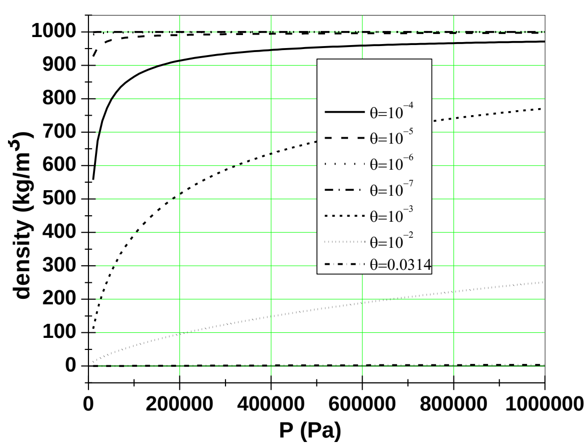


Fig. 7. Variation of the density with pressure.

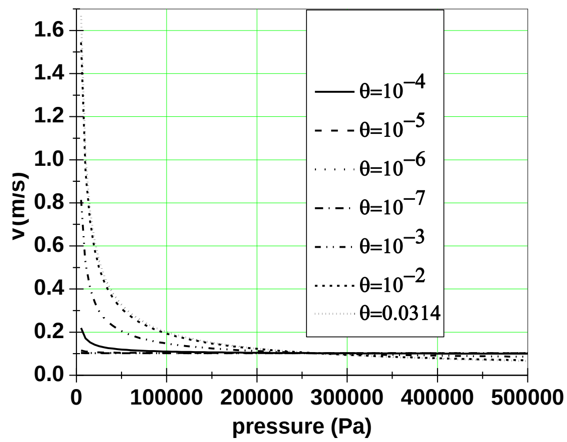


Fig. 8. Variation of the flow velocity with pressure.

In case of the aforementioned observations, we may suggest increasing u_e and thereby increasing the mass flux G, as a solution to the rigid model simulation in the case of Hadj-Taieb and Lili (1998). Furthermore, we are faced with the question about the effects of the initial pressure p_e, and the flow quality. Figure 9 shows the effect of u_e manifested by an increase in the maximum of the velocity profiles mainly at low pressures. Furthermore, by increasing the value of the flow quality θ, the velocity increases and reaches 80m/s, at θ = 0.0314. Reducing the initial pressure from p_e = 263000 Pa to 105000 Pa, we can see on Figure 10 that the profiles ρ (p) are approximately similar to those shown earlier in Figure 7. Clearly, the change in p_e leads to some differences which appear when comparing the profiles of u(p) shown in Figures 8 and 11. However, analysis of both Figures 10 and 11 alone shows that the conditions for applying the homogeneous model are not yet satisfied, because the mass flux G remains less than 2000 kg/(m^2.s).

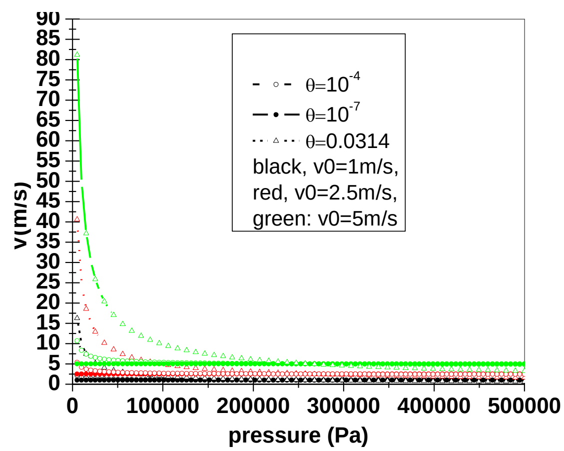


Fig. 9. Effect of u_e and θ upon u(p).

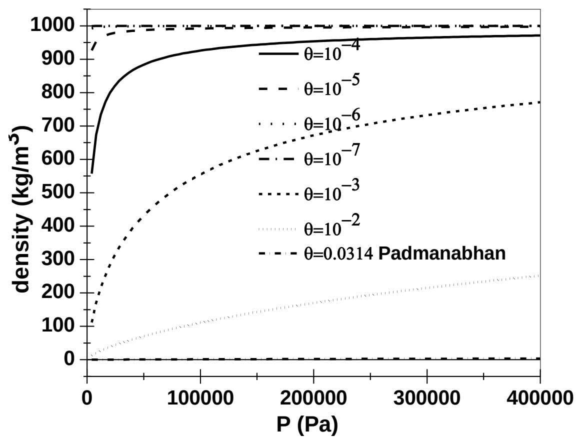


Fig. 10. Effect of the reduction of p_e upon $\rho(p)$.

This is also confirmed when the initial pressure at the pipe inlet is increased up to p_e = 550000 Pa, consequently the density remains unchanged while the fluid velocity increases, particularly when the flow quality is high, θ = 0.0314. We can see this on Figures 12 and 13. However, the condition proposed by Whalley (1996) remains unsatisfied because we still have $G = \rho u < 2000$ kg/(m^2s).

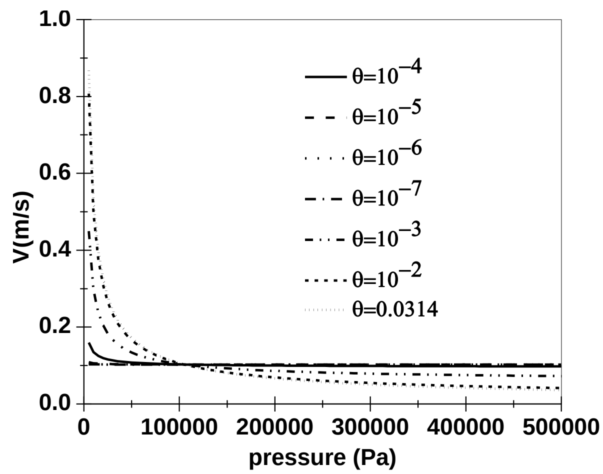


Fig. 11. Effect of the reduction of p_e upon v(p).

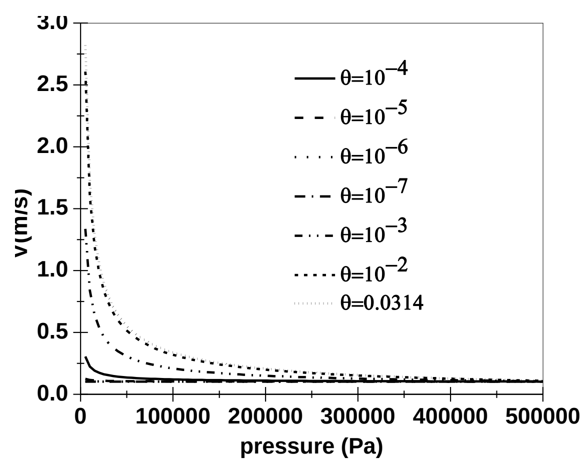


Fig. 12. Effect of the increase of p_e upon v(p).

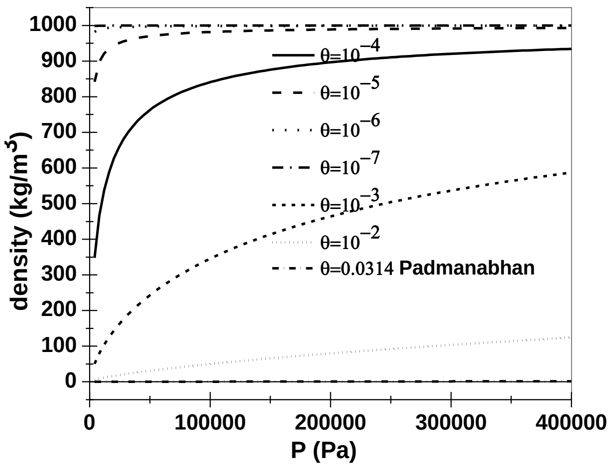


Fig. 13. Effect of the increase of p_e upon ρ(p).

5. Conclusion

In this study we applied the method of characteristics (MOC) to the analysis of homogeneous two-phase flow in pipes. We compared the predictions of the MOC method with experimental data and the predictions of other methods. We observed that the simulation of two-phase flow for the cases of rigid and quasi-rigid models with MOC gives better results than those predicted by the finite difference scheme of Lax Wendroff. We also examined the effect of inlet velocity (u_e) and pressure (P_e), as well as the flow quality, and showed that the impact of these three factors is still unable to overcome the problems of the inapplicability of the homogeneous mixture model as long as the mixture mass flux remains below the well-accepted value of 2000 kg/(m^2s).

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