Multiscale Three-Phase Flow Simulation Dedicated to Model Based Control

Dariusz Choiński, Mieczyslaw Metzger, and Witold Nocoń

Faculty of Automatic Control, Electronics and Computer Science,
Silesian University of Technology,
ul. Akademicka 16, 44-100 Gliwice, Poland
{dariusz.choinski, witold.nocon, mieczyslaw.metzger}@polsl.pl

Abstract. Multiphysics and multiscale three-phase flow simulation is proposed for model based control. Three-phase flow is considered by means of particles movement in a pipe with two-phase gas and liquid vacuum pumping. The presented model and simulation algorithm were implemented using a software system working in real-time mode. The software system can simulate a part of the pipe net with configured pipe profile, pump station and valve parameters and also inlet mixture composition. In addition, the system includes algorithm for pressure control.

Keywords: Multiphisics and multiscale modelling and simulation, three-phase flow, particle movement, model based process control.

1 Introduction

Unsteady two-phase flow is a challenging problem for control engineering. Such type of flow is typical for vacuum pumping technology like vacuum sewerage system (see e.g. [1],[2],[3],[4]) and also in petrol applications (see e.g. [5],[6]). Complexity of the problem is increasing when three phase flow is considered by means of particles movement in a pipe. Such system needs unsteady flow in order to avoid plugging by insoluble parts and particles. The sawtooth lifts, which are used for uphill liquid transport and the same type of pipe profile are necessary for uphill liquid transport and when no valves are opened, no liquid transport takes place, causing medium in the pipe to lie in the low spots. Only part of the pipe cross section is occupied by liquid, so that momentum transfer from air to liquid takes place largely trough the action of shear stresses. Although, the complex system of pipes with complicated profiles as well as with three-phase flow control is difficult for investigation, the control system can improve vacuum pumping system ability with an application of model based control algorithms after simulation for model validation.

Complexity of the model should be adjusted to the requirements of the real-time computing involved in the control system. Even non-standard efforts such as special methods for real-time simulation [7] slightly improve computing possibility for the problem under consideration. Fulfilment of these requirements can help modelling of multiphysics and multiscale system (see e.g. [8], [9], [10]). Multiphysics-multiscale approach couples

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calculations at different scales for two-phase flow and particle movement as the third phase. A specially rearranged three-phase model with simulation implementation for control purposes is presented in this paper. Mathematical descriptions such as two-phase gas-liquid modelling, modelling particle movement in the liquid pipeline, modelling two phase-flow through pipe inclinations, already known when investigated separately, have been implemented together for the presented investigations.

The presented model and simulation algorithm were implemented using a software system working in real-time mode. The software system can simulate a part of the pipe net with configured pipe profile, pump station and valve parameters and also inlet mixture composition. The system also includes algorithm for pressure control. Multiscale approach reduced the number of parameters sent between pipe sections. This gives the ability to connect particular programs using TCP/IP protocol in different computers for parallel simulation of a wide net of pipes and valves.

2 Problem Under Consideration and Two-Phase Flow Mathematical Model

The paper deals with a mechanized system of pipe transport that uses differences in gas pressure to move the liquid. The system requires a normally closed vacuum valve and a central vacuum pump station. The pressure difference between atmosphere and vacuum becomes the driving force that propels the liquid to the vacuum station. For two-phase flow (gas and liquid) the momentum equations can be written separately for each phase and such description is sufficient for the present properties of the whole flow. In such a model the phases are treated as if they were separated and as if they were flowing in unspecified parts of the cross section. Both phases have different velocities and fluid viscosities. The gas compression is the main reason to differ air velocity from water velocity [11][12][13] and it is considered in the presented simulation. The presented model was developed under assumption that is based on vacuum pipes network designer instruction. Such approach gives possibilities of easier model calibration and validation. The pressure drop caused by separated phase flow can be correlated using the Lockhart-Martinelli method [14,15]. The pressure drop multipliers Φ_l^2 and Φ_g^2 are defined as follows:

$$X^2 = \frac{\Phi_g^2}{\Phi_l^2} = \frac{\dfrac{\left(\frac{\Delta P}{L}\right)_{Mix}}{\left(\frac{\Delta P}{L}\right)_g}}{\dfrac{\left(\frac{\Delta P}{L}\right)_{Mix}}{\left(\frac{\Delta P}{L}\right)_l}} = \frac{\left(\frac{\Delta P}{L}\right)_l}{\left(\frac{\Delta P}{L}\right)_g}, \tag{1}$$

where: $\left(\frac{\Delta P}{L}\right)_{Mix}$ - pressure drop gradients along the pipe section which can be measured and controlled. Next gradients are calculated and depend on liquid and gas phase correlation,

$\left(\frac{\Delta P}{L}\right)_l$ - pressure gradient for flow of liquid along the pipe section,

$\left(\frac{\Delta P}{L}\right)_g$ - pressure gradient for flow of gas along the pipe section.

The pressure drop gradient along the whole pipe is evaluated based on the measured absolute pressure in a vacuum station, absolute pressure in a pipe connected to a valve or to previous part of pipe net and also boundary conditions determined by pipe profile inclination angle. Pressure gradient for the flow of liquid and gas along the pipe section is calculated from Lockhart-Martinelli parameter X^2. The parameter X^2 may be evaluated in terms of air mass friction [14]:

$$x = \frac{G_g}{G_{Mix}} \tag{2}$$

G_g [kg/s m^2] – the superficial mass flux of gas is calculated from the volume flow of the vacuum pump in pump station multiplied by density of gas corrected with pressure, temperature and humidity using Brietty-Bridgeman real gas state equation [14,15]. The simulation procedures should take advantage of the fact that gas is compressible and its specific volume is a function of pressure, temperature and humidity. For example, the absolute pressure varies between 15kPa and 65 kPa, specific volume of air changes between 5.61 m^3/kg and 1.294 m^3/kg, (ratio 4.3:1). For wet air (humidity 80%) the ratio is 4.5:1. Liquid is considered incompressible.

G_{Mix} [kg/s m^2] – the superficial mass flux of gas mass and liquid mass measured in the pump station.

G_l=G_{Mix}-G_g [kg/s m^2] – the superficial mass flux of the liquid measured in the pump station as volume of liquid multiplied by liquid density corrected to the ambient temperature. The mass of gas and liquid is used for model validation. These parameters are investigated during real system design.

The Lockhart-Martinelli parameter X^2 is defined as:

$$X^2 = \left(\frac{1-x}{x}\right)^{1.8}\left(\frac{\rho_g}{\rho_l}\right)\left(\frac{\mu_l}{\mu_g}\right)^{0.2} \tag{3}$$

where:

ρ_g – gas density [kg/m^3], ρ_l – liquid density [kg/m^3], μ_g – dynamic gas viscosity [Pa sec], μ_l – dynamic liquid viscosity [Pa sec].

The separate side-by-side flow of gas and liquid is considered. When the vacuum valve is closed, liquid is at the bottom of the pipe, respectively to sawtooth profile of the pipe. The pipe is divided into sections with similar liquid level and pressure loss in the steady state. Initial conditions of the liquid level can be adjusted during simulation. Additional liquid level simulates solid wastes, the velocity of which is much slower than liquid linear velocity.

The liquid and air momentum, M_l and M_g respectively, can be calculated as follows:

$$M_l = G_l S \ , \tag{4}$$

$$M_g = G_g S \ , \tag{5}$$

where: S – cross section of the pipe [m^2], S_a – cross section occupied by gas [m^2], S_w – cross section occupied by liquid [m^2].

For further consideration, void fraction α and mass fraction of gas ω are used and are defined as follows:

$$\alpha = \frac{S_g}{S} \ , \tag{6}$$

$$\omega = \frac{M_g}{G_{Mix} S} \ . \tag{7}$$

The above equations are valid, assuming the following condition:

$$\frac{d\omega}{dx} = 0 \ . \tag{8}$$

The pipe is subdivided into n sections of length L. The liquid level in a section is the same as for boundary condition. For the separated flow, assuming equilibrium, force balance equation for gas phase is as follows:

$$-\left(\frac{dP}{dL}\right)_g = \frac{2K_g \left(\frac{d\omega G_{Mix}}{\mu_g}\right)^{-m} \omega^2 G_{Mix}{}^2}{d\rho_g} \ , \tag{9}$$

where: d – internal tube diameter [m].

For laminar flow K_g=*16* and *m=1*, for turbulent flow K_g=*0.046* and *m=0.2*. The Reynolds number necessary for choosing of the flow type is calculated as follows:

$$\mathrm{Re}_{Mix} = \frac{G_{Mix} d}{\omega\mu_g + (1-\omega)\mu_l} \ . \tag{10}$$

Pressure drop calculation for liquid phase is based on Hazen-William formula [14,15]. This formula is used as a design guide for vacuum sewerage and coefficients for several tube types are described. Generally, an empirical relationship for the friction head loss h_L [m] in a PVC pipe segment typically used for vacuum sewerage, may be expressed in a form:

$$h_l = \frac{1.2128}{d^{4.87}} \left(\frac{G_l}{\rho_l}\right)^{1.85} \ . \tag{11}$$

The pipe is subdivided into sections with varying cross section occupied by the liquid (see Fig. 1).

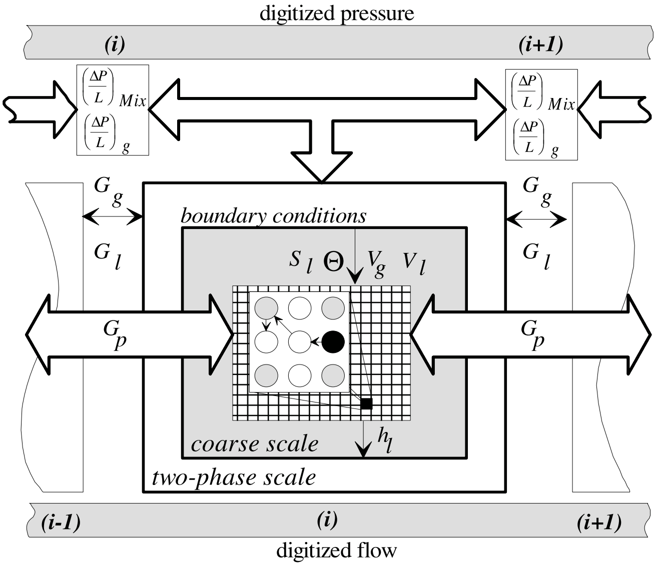

Fig. 1. Multiscale diagram of computing; l – liquid, g – gas, Mix – gas+liquid, p – particle, S – cross section of the pipe, Θ - pipe inclination angle, h – friction head loss, G – superficial mass flux, V – velocity, P – pressure, L – pipe segment length.

The initial conditions for the simulation should start from the set up of the liquid volume in the particular section of the pipe in the steady state. The program automatically calculates the slop of the pipe section properly to the volume in the previous, current and the next part. This set up assumes the pressure drop profile for gas phase and the friction head loss. The following initial conditions are: maximum absolute pressure of the pump station, buffer capacity of the vacuum pump, minimum start pressure for valve opening and the time period during the valve closure. Volume inserted to the pipe while the valve is opened and particle contents are established as well. The valve is located at the first pipe segment, while the pump station is located at the last segment. The output from the pipe can be connected not only to the pump station, but also to the next pipe segment or another simulated system using TCP/IP protocol. Respectively, the first segment can be connected to the last segment of another pipe. For clear presentation of flow, the pipe is presented as straight, while the effect of the sawtooth profile are the varying liquid levels (see Fig. 2).

In the particular steps of the simulation algorithm for the two-phase flow scale, the following values are calculated:

- Static absolute pressure of the gas phase in the relationship to pressure drop profile.
- Differential pressure for pipe segment
- Density and viscosity of gas and liquid phase

- Superficial mass flux of gas and liquid

- New volume of liquid in the pipe section
- Continuity of equation by liquid phase mass balance in the whole pipe is checked
- Pressure correction for proper mass balances
- Medium velocity for mixture, gas and liquid phase with respect to the pipe cross section
- Calling the coarse scale for friction head loss correction

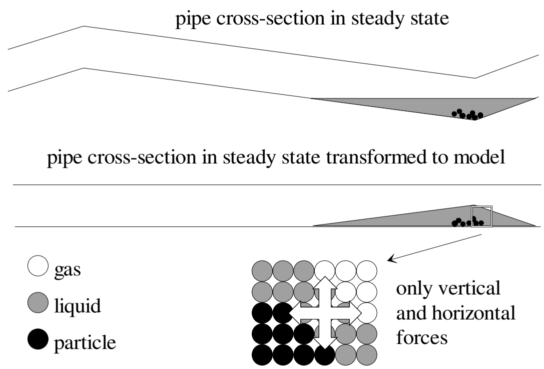

Fig. 2. Model simplifying for coarse scale

3 Multiscale Particle Motion Simulation

For particle motion simulation 2-D coarse scale is implemented. The stratified, annular and slug flow are considered. Types of two-phase flows are determined by gas and liquid superficial mass flux, cross section of pipe occupied by liquid and the inclination angle of pipe profile. The coarse grid is used for simulation of bubble and particles motion, pressure drop for liquid phase and friction head loss. Simulated bubble movement and local liquid velocity enables calculation of particle behaviour: motion and sedimentation. The grids are considered in particular pipe segments with assumption that density and viscosity are constant, enabling simple momentum calculation. For example, in the pipe with inner diameter of 0.05 [m] the boundary conditions are as follows [2]: Stratified flow for: $G_g<2$ and $G_l<100;$ Annular flow for: $G_g >10$ and $G_l <1000;$ Slug flow $10> G_g >2$ and $100< G_l <100.$

Resolution of the grid can be different for the particular pipe segment and is selected to the estimated gas bubble diameter based on empirical investigation. The grid is considered for the particular pipe segment as far as bubble behaviour is concerned and for the whole pipe as far as particle motion and sedimentation are concerned.

The matrix construction for the grid representing liquid and gas phase in pipe for investigation of the bubble motion in pipe segment starts from calculation of liquid level inclination angle to the gas velocity vector and onset slug flow based on empirical equation [15]:

$$G_g \geq G_l + 0.487\left[\left(\frac{\rho_l}{\rho_g}\right)gh_g\right]^{\frac{1}{2}}, \tag{12}$$

where: h_g – the height of the gas pocket during slug flow.

For the accurate friction head loss correction in the two-phase slug flow the prediction of the liquid holdup is necessary. The dimensionless correction factor R_S equals [16]:

$$R_S = \exp\left[-\left(0.45\Theta + 2.48 \bullet 10^{-6}\frac{\rho_l V_{Mix} d}{\mu_l}\right)\right] \tag{13}$$

where: Θ - the pipe inclination angle in radians (0..1.57)

In practice, mixture velocity V_{Mix} value is usually low hence practically, the correction factor mainly depends on pipe inclination angle. The most important factor is slug flow condition that is described by gas bubble to liquid motion. The matrix for pipe segment is divided into a moving window with resolution 3x3. Motion of this window is parallel to the liquid velocity vector. Matrix in the window describes simple relation between liquid and gas elements representative for investigated stratified, annular and slug flow. In this step, elements of the matrix which represent particles are moving parallel to liquid elements. In case of the slug flow, scrolling direction is upwards, otherwise it is downwards.

The proper gas, liquid and particle volume, summarized momentum and maximum height of the gas pockets for slug flow are checked after scrolling the whole segment. The matrix constructed by contact of matrixes representing pipe segments is used for investigation of particle motion. In such investigations, a moving window is also used but in opposite direction and dimension of the window along the pipe is 6, across the pipe it is 3. For every matrix element that represents particle, a velocity vector based on the near 17 elements is calculated and this vector determines a target matrix element. After that, the matrix element that represents the particle is being interchanged with target element. Also, liquid volume in pipe segment is calculated and corrected.

The last step is calculation of friction head loss factor which is proportional to the value derived using the above equation and the height of the gas pocket after particle motion correction. During stratified flow of particles the gravity force vector is considered. For gas phase in this flow case, the most significant force vector depends on uplift pressure.

Simulation program is prepared as a stand-alone application dedicated only to the presented model as a real-time simulator of the distributed object with controller and communication interface for real controller connection. Calculation complexity, real-time simulation and 3D graphs for on-line presentation of the distributed parameters object require a program that is well optimized for speed and size.

4 Selected Results and Concluding Remarks

The simulation investigations show, that the best way to force movement of undesirable particles in the inclined pipes is to destabilise the flow (see Fig. 3).

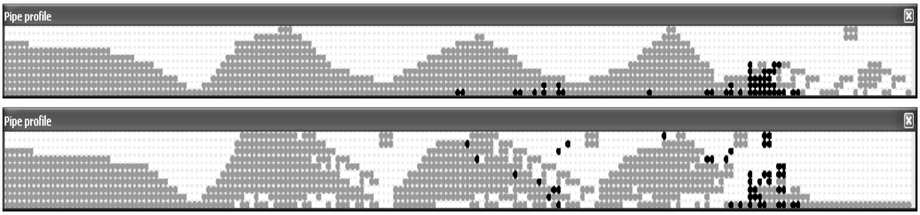

Fig. 3. Visualization of the pipe segment (with reduced resolution for print); start of the unsteady process (top), movement of the particles (bottom)

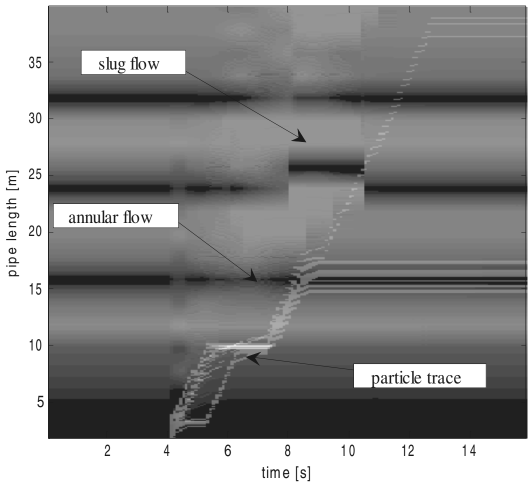

Fig. 4. Time changes of normalized density for three-phase flow. Vacuum being controlled at the pipe output. The valve is opened at t=4 s.

For clear presentation of flow, the pipe is presented as straight, while the effect of the sawtooth profile are the varying liquid levels. At the beginning of simulation experiment, a number of particles lie at the bottom of sawtooths (black points), whereas the liquid at the end of the pipe becomes unsteady (white bubbles in the liquid). The transient response presented at the bottom window shows the situation in which some of the particles jump over the sawtooths and move in the desired direction.

Additional information is presented in 3D diagrams, in which the x-t profiles are presented (see Figs. 4 and 5).

The x variable in Figs. 4 and 5 represents the normalized density at the pipe cross section, hence the ratio of the averaged density for three phases and liquid density. For higher densities, the color on the plot is darker. For steady state, the density gradient corresponds to the pipe leveling. “averaged color” corresponds to annular flow, hence to the mixing of different phases. A clearly visible color gradient displaced with respect to the pipe leveling accompanies the slug flow. Additionally, different type of visualization of experimental studies are plots of liquid phase flow along the pipe (see for example Fig. 6).

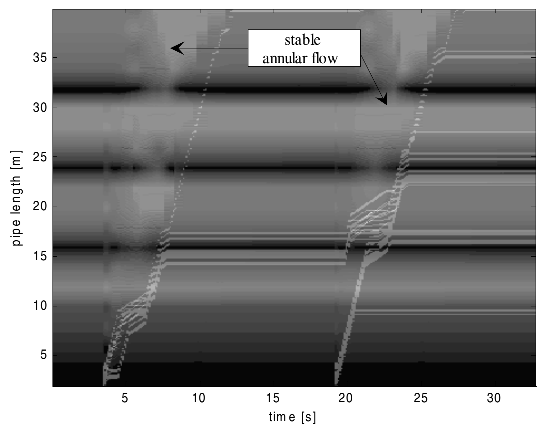

Fig. 5. Time changes of normalized density for three-phase flow. Vacuum being controlled along the pipe. The valve is opened at t=4s and t=18s. A stable annular flow is present, that decreases the hydraulic resistance and enables flow of solid particles.

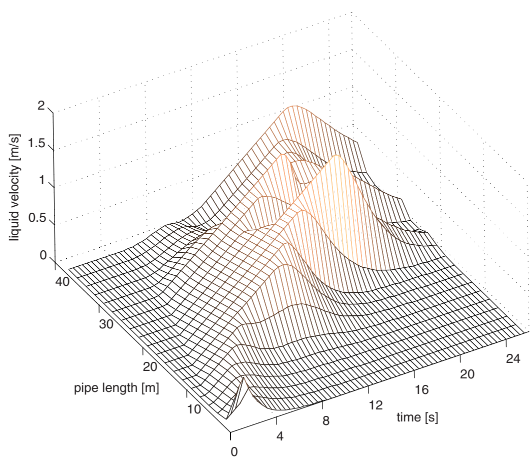

Fig. 6. Linear velocity of liquid-phase flow in case of vacuum being controlled along the pipe

The process operator should make the appropriate decision based on the simulated control system with monitoring and visualisation. A real-time simulator of the process improves the optimal operating control. The proposed software system is dedicated as a simulation support for model based operating control and monitoring. In this case, the operator can check control decisions using the simulator and find the most appropriate decision. In the mode of the reduced coarse grid resolution, the proposed system can also be helpful for direct digital control based on PC-embedded controller.

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