EXPERIMENTAL AND THEORETICAL STUDY OF STEAM CONDENSATION INDUCED WATER HAMMER PHENOMENA

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Abstract *We investigate steam condensation induced water hammer (waha) phenomena and present experimental and theoretical results. Some of the experiments were performed in the PMK-2 facility, which is a full-pressure thermohydraulic model of the nuclear power plant of VVER-440/312 type and located in the Atomic Energy Research Institute Budapest, Hungary. Other experiments were done in the ROSA facility in Japan.*

On the theoretical side waha is studied and analyzed with the WAHA3 model based on two-phase flow six first-order partial differential equations that present one dimensional, surface averaged mass, momentum and energy balances. A second order accurate high-resolution shock-capturing numerical scheme was applied with different kind of limiters in the numerical calculations. The applied two-fluid model shows some similarities to Relap5 which is widely used in the nuclear industry to simulate nuclear power plant accidents. Experimentally measured and theoretically calculated waha pressure peaks are in qualitative agreement.

I. INTRODUCTION

Safety of nuclear reactors is a fundamental issue. Nuclear and thermo-hydraulic processes in the active zone of modern reactors are well known and well-controlled, explosions are out of question. However, violent unwanted thermo-hydraulic transients in the primer loop may cause serious derangement or pipe breakage. Such an unplanned transient is the steam condensation induced water hammer(waha). In thermal loops of atomic reactors or in other pipelines where water steam and cold water can mix, quick and dangerous transients can occur causing explosions which mean high financial expenses or even cost human lives.

In the following we will introduce the ROSA [1] and the PMK-2 facility [2] which is an integral experimental device and capable to produce waha effects.

On the other side we present the WAHA3 [3] model we use, which is a complex physical model suitable to simulate various quick transients in single and two-phase flows.

In the last two decades the nuclear industry developed a few complex two-phase flow-codes like Relap5 [4], Trac [5] or Cathare [6] which are feasible to solve safety analysis of nuclear reactors and model complicated two-phase flow transients.

The model, WAHA 3 [7] is very similar to Relap5. This means that the conservation equations and all the applied correlations are essentially the same. The main difference between the above mentioned models and our WAHA3 code is basically the applied numerical scheme; other commercial codes have a ratio of spatial and time resolution $\Delta x / \Delta t$ which describes usual flow velocities. This code, however is capable of capturing shock waves and describes pressure waves which may propagate quicker than the local speed of sound. To our knowledge there is no special model and computer code for numerical simulation of water hammer in the field of nuclear thermal-hydraulics.

WAHA3 model can successfully reproduce the experimental data of different one- or two-phase flow problems such as ideal gas Riemann problem, critical flow of ideal gas in convergent-divergent nozzle, column separation or cavitation induced water hammer or even rapid depressurization of hot liquid from horizontal pipes. [3]

II. EXPERIMENTAL SETUPS AND THEORY

In the following section we give a brief overview of the Hungarian PMK2 and the Japanese ROSA where the water hammer experiments were performed. After that our theoretical model WAHA3 will be briefly introduced.

II.A PMK2

The PMK-2 facility is located at the KFKI Atomic Energy Research Institute (AEKI) Budapest, Hungary [2] . It is a full-pressure scaled down thermohydraulic model of the primary and partly the secondary circuit of the nuclear power plant of VVER-440/213 type (VVER is a Hungarian abbreviation of the water-water energetic reactor). It was primarily designed for the investigation of off-normal transient processes of small-break loss of coolant accidents. Between 1985 and 2007 there were 55 different experiments performed on the apparatus. The group of transients is as follows 7.4 % cold leg breaks(15 tests), cold leg breaks of different sizes(10 tests), hot leg breaks and primary to secondary leaks(10 tests); tests for natural circulation characteristics and disturbances(10 tests); plant transients and accidents (10 tests). Results of experiments were used to validate thermohydraulical system codes as ATHLET, CATHARE and REALP5 for VVER applications.

Considering the scaling ratio interval and the financial possibilities of the country, a 19 rod core model with 2.5 m heated length was selected which gives a power ratio of 1:2070 (39.312:19 ~ 2070) and, therefore, the overall volume scaling ratio is also 1:2070. The operating pressure of the PMK-2 is 12.3 MPa and the core thermal power is 664 kW. The heat loss for the PMK-2 facility is about 3.6 percent of the nominal heat power. Due to the importance of gravitational forces in both single- and two-phase flow the elevation ratio is 1:1. Other important similarity properties like the Richardson, Stanton, Froude and the Nusselt numbers are 1:1 as well. There are 10 integral type facilities for PWR's (Pressurized Water Reactors) and VVER's in the world like the American LOFT, the ROSA-IV in Japan, the PACTEL facility in Finland or the Hungarian PMK-2. VVERs are slightly different from PWRs of the usual design and have a number of special features, viz: 6-loop primary circuit, horizontal steam generators, and loop seal in hot and cold legs, safety injection tank set-point pressure higher than secondary pressure.

The steam pressure on the steam generator side is 4.6 MPa. The WAHA experimental setup is connected into the steam line of PMK-2 and located on the top of the integral facility. The experimental setup is basically a horizontal pipe section of 5 m length and 193 mm internal pipe diameter initially filled with vapor that is supplied from the dome of the steam generator of the PMK-2. The other side of the test device is connected to the condenser unit of PMK-2 which substitutes turbine of the real power plant. Both ends of the WAHA tube are further equipped with inertia blocks of 200 kg each serving a 90 deg bend in the same time. The test section can be isolated by two valves; one is located in the connection with the head of the steam generator, and the other in the connecting line towards the condenser. For the flooding, a cold water tank with a volume of 75 l is installed and pressurized with air.

II.B ROSA

The second experimental facility which will be introduced is the Japanese Rosa.

OECD/NEA ROSA Project Test 2 (ST-WH-05, 06, 07, 08, 09, 10 and 11, conducted by JAEA) was performed on April 11 and 12, August 28 and 29, and September 5 and 6, 2007 by using the Large Scale Test Facility (LSTF) [1] in the Japan Atomic Energy Agency (JAEA). The objective of this test is to obtain detailedthermal-hydraulic transient data concerning condensation-induced water hammer (CIWH) in a horizontal branch pipe connected to the LSTF vessel downcomer. The schematic view of a CIWH in a horizontal pipe is shown in Fig. 1. The data is in particular used to study the effect of the system pressure on the CIWH characteristics such as the intensity of the CIWH pressure pulse. It is important for the nuclear safety, since room-temperature water is injected by ECCS (Emergency Core Cooling System) including passive safety system even at high pressure condition.

This study covers the CIWH induced at two-phase counter current flow in a horizontal pipe. The liquid phase flow simulates the room-temperature water flow injected by ECCS. The vapor phase flow simulates the saturated steam flow driven by the condensation on the room-temperature water. Such two-phase condition may be appeared at the ECCS injection line, when the water injection rate is decreased. A horizontal pipe is employed as the test section for CIWH tests. The dimensions of the test section, made of stainless steel, are 2050 mm in length, 66.9 mm in inner diameter and 11 mm in pipe wall thickness. One end of the test section is horizontally connected to the LSTF horizontal nozzle named N-18c whose center elevation is EL+3945. The nozzle length is 290 mm from the LSTF downcomer inner surface, and the inner diameter is the same as the test section inner diameter. Accordingly, they form an about 2.3 m long horizontal pipe. The other end of the test section is closed using a sealing plate. The room-temperature water stored in the LSTF RWST tank is injected to the bottom of the test section near the closed end using the LSTF high pressure injection system (HPI). The water is discharged to the LSTF downcomer through the test section. When the downcomer liquid level is much lower than the bottom elevation of the test section, the water falls freely into the downcomer would affect the water fall under high water supply conditions.

The CIWH tests were performed at the system pressure of 0.35, 1.0, 2.8, 4.4, 5.5 and 7.0 MPa. The maximum system pressure of 7.0 MPa is determined in consideration for the result of the past LSTF test. The result shows that CIWH is induced at 4.1 MPa, although the test section is not suitable for the CIWH test. Thus, higher system pressure than 4.1 MPa is employed as the maximum system pressure.

The minimum system pressure of 0.35 MPa is the lowest system pressure that is controllable. Therefore, since the heat removal of the LSTF primary loop is performed by the steam generators, the primary pressure has to be comparatively larger than the secondary pressure which is set to atmospheric pressure. The flow rates about 0.1, 0.3 and 0.9 kg/s at the room-temperature were employed as the test condition. According to the LSTF tests experience, the CIWH may be induced near about 0.3 kg/s. The flow rates about 0.1 and 0.9 kg/s are lower and upper bound at supply flow rate; respectively, in order to keep the balance between the supply flow rate and the discharge flow rate. The flow rate is controlled by the pump operation of the high pressure injection system (HPI). The water temperature of the former and the latter is about 290 K and about 305 K, respectively.

II.C Theory

There are large number of different two-phase flow models with different levels of complexity [8,9] which are all based on gas dynamics and shock-wave theory. In the following we present the one dimensional six-equation equal-pressure two-fluid model.

The density, momentum and energy balance equations for both phases are the following:

$$\frac{\partial A(1-\alpha)\rho_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f(v_f-w)}{\partial x}=-A\Gamma_g \qquad (1)$$

$$\frac{\partial A\alpha\rho_g}{\partial t}+\frac{\partial A\alpha\rho_g(v_g-w)}{\partial x}=A\Gamma_g \qquad (2)$$

$$\frac{\partial A(1-\alpha)\rho_f v_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f v_f(v_f-w)}{\partial x}+A(1-\alpha)\frac{\partial p}{\partial x}-A\cdot CVM$$
$$-Ap_i\frac{\partial\alpha}{\partial x}=AC_i|v_r|v_r-A\Gamma_g v_i+A(1-\alpha)\rho_f cos\theta-AF_{f,wall} \qquad (3)$$

$$\frac{\partial A\alpha\rho_g v_g}{\partial t}+\frac{\partial A\alpha\rho_g v_g(v_f-w)}{\partial x}+A\alpha\frac{\partial p}{\partial x}+A\cdot CVM+Ap_i\frac{\partial\alpha}{\partial x}=$$
$$-AC_i|v_r|v_r+A\Gamma_g v_i+A\alpha\rho_g cos\theta-AF_{g,wall} \qquad (4)$$

$$\frac{\partial A(1-\alpha)\rho_f e_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f e_f(v_f-w)}{\partial x}+p\frac{\partial A(1-\alpha)}{\partial t}+\frac{\partial A(1-\alpha)p(v_f-w)}{\partial x}$$
$$=AQ_{if}-A\Gamma_g(h_f+v_f^2/2)+A(1-\alpha)\rho_f v_f g cos\theta \qquad (5)$$

$$\frac{\partial A\alpha\rho_g e_g}{\partial t}+\frac{\partial A\alpha\rho_g e_g(v_f-w)}{\partial x}+p\frac{\partial A\alpha}{\partial t}+\frac{\partial A\alpha p(v_f-w)}{\partial x}$$
$$=AQ_{ig}+A\Gamma_g(h_g+v_g^2/2)+A\alpha\rho_g v_g g cos\theta. \qquad (6)$$

Index f refers to the liquid phase and index g to the gas phase. Nomenclature and variables are described at the end of the manuscript. Left hand side of the equations contains the terms with temporal and spatial derivatives.

Hyperbolicity of the equation system is ensured with the virtual mass term CVM and with he interfacial term (terms with p_i). Terms on the right hand side are terms describing the inter-phase heat, mass (terms with Γ_g vapor generation rate) volumetric heat fluxes Q_{ij} , momentum transfer (terms with C_i), wall friction $F_{g,wall}$, and gravity terms. Modeling of the inter-phase heat, mass and momentum exchange in two-phase models relies on correlations which are usually flow-regime dependent.

The system code RELAP5 has a very sophisticated flow regime map with a high level of complexity. WAHA3 however has the most simple flow map with dispersed and horizontally stratified regimes only, because the uncertainty of steady-state correlations in fast transients are very high.

A detailed analysis of the source terms can be found in Tiselj et al. [3,7]

Two additional equation of states (eos) are needed to close the system of equations

$$\rho_k=\left(\frac{\partial\rho_k}{\partial p}\right)_{u_k}dp+\left(\frac{\partial\rho_k}{\partial u_k}\right)_p du_k. \qquad (7)$$

Partial derivatives in Eq. 7 are expressed using pressure and specific internal energy as an input. The table of water and steam properties was calculated with a software from UCL. [10]

The system of Eqs. (1-6) represents the conservation laws and can be formulated in the following vectorial form

$$\mathbf{A}\frac{\partial\mathbf{\Psi}}{\partial t}+\mathbf{B}\frac{\partial\mathbf{\Psi}}{\partial x}=\mathbf{S} \qquad (8)$$

where $\mathbf{\Psi}$ represents the non-conservative variables
$\mathbf{\Psi}(p,\alpha,v_f,v_g,u_f,u_g)$

A, B are matrices and **S** is the source vector of non-differential terms. These three terms can be obtained from Eq. (1-6), with some algebraic manipulation.

In this case the system eigenvalues which represent wave propagation velocities are given by the determinant det(**B**- λ **A**). An improved characteristic upwind discretization method is used to solve the hyperbolic equation system (Eq. 8). The problem is solved with the combination of the first-and second-order accurate discretization scheme by the so-called flux limiters to avoid numerical dissipation and unwanted oscillations which appear in the vicinity of the non-smooth solutions. Exhaustive details about the numerical scheme can be found in LeVeque [11]

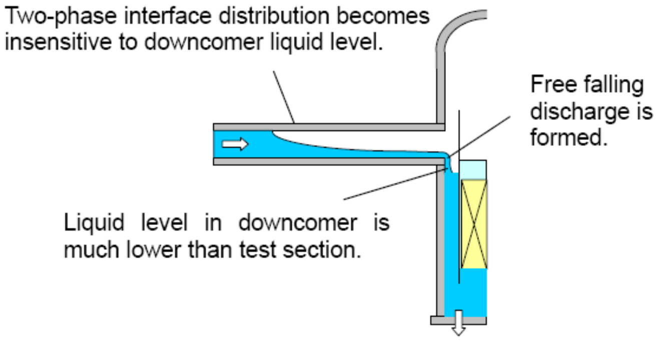

Fig. 1. A shematic sketch of the ROSA WAHA experimental tube.

III. Results

Figure 2 presents one of the experimentaly measured WAHA pressure peaks in the OECD/NEA ROSA Project. There are various measuremenets done, we analyse only one of them in the following.

The stem pressure was 2.8 MPa with 503 K temperature. The cold water temperature was 305 K with a flooding velocity of 0.088 m/s.

The measurement took 1320 seconds. It might be true from the experimental setup and from the results, that large number of stem condensation induced WAHA events happened. In contrast to other WAHA experimental setups here, the horisontal tube is opened at both ends, hence it is possible to have flow conditions when the tube cannot be filled up with water and there is a relatively long time interval when large and long horisontaly stratified flow regime could exist. Our detailed analysis showed that there is about a 38 second long time interval when continous “steam bubble capture” mechanism occur on the surface of the horisontaly stratified flow which might be responsible for a large number of WAHA pressure peaks. Figure 3 shows our results obtained from numerical simulation where numerous WAHA peaks can be detected for the above mentioned flow system.

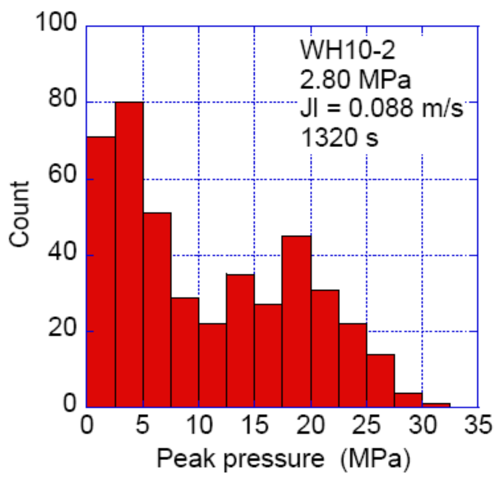

Fig. 2 WAHA Peaks measured in the ROSA Project.

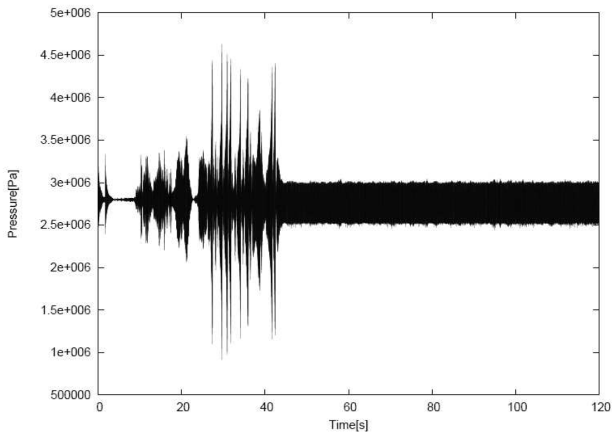

Fig. 3. Time history of the pressure peaks for the ROSA measurement obtained from our numerical simulation.

After 38 seconds the tube will be filled up with water, at this flow rate and only the very last part of the tube has some free steam void fraction, which might be responsible for additional steam condensation and pressure peaks.

Our experience and private communication with the author of the model [3,7] say that pressure peaks after the filling up is presumably a numerical artefact. These results are extremely sensitive to the given flow velocity, a tiny steam mass flow from the downcommer against the cold water can produce further pressure peaks up to 120 seconds.

The authors of this study tried to find out what was exactly measured in this ROSA project, and how these large number of pressure peaks occure, we can only imagine that large number of reflected pressure waves were also detected as independent pressure peaks. Such an artefact was detected and analysed in our last study[12].

We could not perform calculations up to 1320 seconds only up to 120 due to the extreme number of data. It is worth to mention that a WAHA pressure peak has a 2ms half width which means extremely high time resolution and output. Further work is in progress to clear out all the detailes.

As a second system we investigated and analysed the measurements done at PMK2 in Budapest.

Measurements were done at 3 different stem pressures, with 6, 10 and 15 bar. Fig. 4 show the time history of the measured pressure peaks for 15 bar. Contrary to our former experiments [12] two or more independent WAHA events can happen in this new apparatus with a longer (former 3 meter length, now 5 meter length) horisontal tube. A careful investigation of the dynamics of the void fraction along the tube during the flooding clearly shows that in a longer tube there is enough room for two steam bubble formation. Our former study [12] gives a detailed analysis of the “bubble capture mechanism”. Figure 5. shows our results obtained from numerical simulation for the above mentioned experiment. Unfortunatelly, we can not found 2 independent overpressure peaks with 60 and 45 bar but two peaks with 133 and 85 bar overpressure. A deeper analysis of the void fraction showed that indeed two independent steam bubbles are formed and vehemently captureed during the flooding. The absolute value of the pressure peaks and the time lag between the two pressure peaks are again very sensitive to the flooding velocity. Further work is in progress, right now we investigate the question of the steam mass flow rate from the steam generator. If we consider steam flow against the cold water(which cannot be measured till now, but should be the physial case) than the relation of the two peaks can be changed.

IV. CONCLUSIONS

We presented and analysed water hammer experimental results performed at the ROSA and the Hungarian PMK-2 experimental facility. Where the later is a full pressure scaled down model of the primary and partly the secondary loop of the national Nuclear Power Plant equipped with the VVER-440/312 type.

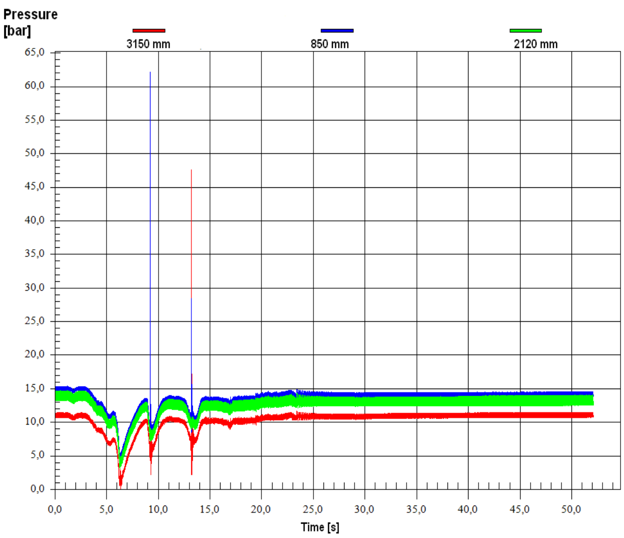

Fig 4. Time history of the pressure peaks at 850, 2120 and 3150 mm from the left end of the horizontal pipe.

With the help of a one dimensional two-phase flow model we investigated the steam condensation induced water hammer phenomena. With a detailed analysis of the pressure wave propagation and the dynamics of the vapor void fraction along the pipeline

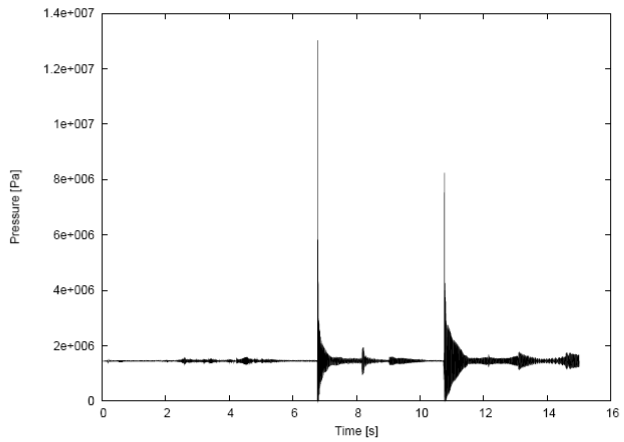

Fig. 5. Time history of the pressure peaks for the PMK2 measurement obtained from our numerical simulation.

the "steam bubble collapse" mechanism is identified which is responsible for for steam condensation induced water hammer in horizontal pipes.
Steam bubble collapse induced water hammer events happen if the following six conditions meet:[13]

1) the pipe must be almost horizontal (max. pipe inclination must be less than 5 degree)
2) the subcooling must be greater than 20 C^{o}
3) the L/D (length-to-diameter ratio of the tube) must be greater than 24
4) the velocity must be low enough so that the pipe does not run full, i.e. the Froude number must be less than one
5) there should be a void nearby
6) the pressure must be height enough so that significant damage occurs, that is the pressure should be above 10 atmospheres.

Contrary to older WAHA experiments the ROSA and the new PMK2 setups can produce more than a single WAHA event which is a new feature for us an presented above. Unfortunatelly, we do not have a fulltime numerical simulation of the ROSA experiment but our investigation might give us a clearer sight about the physical phenomena which is happening behind.

As a second system we investigated the experimental data from the new WAHA experimental facility, which was built in the Hungarian PMK-2 integral experimental device right now. The geometry is basically the same as mentioned in our former study[12] but a much larger horizontal pipe was raised with 5 meter lengths and 25 cm in diameters. First experiments gave water hammer events with 60-80 bar peak pressures, which are much smaller than in previous experiments. On the other side, poor theoretical analysis show that appearance of 350 bar overpressure peaks are not impossible. We explain such huge discrepancies with the fact that waha events are very sensitive to initial flooding water velocity. The new experimental system has another peculiarity, two or even three independent waha events happen one after another separated by 10 seconds or more. A careful investigation of the dynamics of the void fraction along the tube during the flooding clearly shows that in a longer tube(now 5 meters long former was only 3) there is enough room for two steam bubble formation. Our recent analysis shows that it is even possible to obtaine two independent WAHa pressure peaks via numerical simulation. Besides the flooding velocity, the mass flow of the steam from the dome of the steam generator is a critical physical parameter as well. Unfortunately this parameter cannot be measured till now, but serious work is in progress to recondition this incompleteness.

Further theoretical investigations are in progress to illuminate all details.

In contrast to large system codes like REALP5 or Trac we have the source code of WAHA3 which is transparent and flexible to apply it to other two-phase flow systems.

Recently, we modified our model and created a realistic two-phase liquid-steam table for mercury. We performed calculations to simulate pressure waves and cavitation effects in the planned European Spallation Source (ESS)[14].

As a long term interest we also plane to investigate other liquid metal (e.g. bismuth-lead eutectic) systems[15] or liquid helium which can be interesting as a cooling media for new type of nuclear reactors. Liquid metal systems can operate on low (some bar) pressure and have much larger heat conductivity than water which can radically enhance thermal efficiency.

NOMENCLATURE

A pipe cross section (m^2)

C_i internal friction coefficient (kg/m^4)

CVM virtual mass term (N/m^3)

e_i specific total energy [$e = u + v^2/2$] (J/kg)

$F_{g,wall}$ wall friction per unit volume (N/m^3)

g gravitational acceleration (m/s^2)

h_i specific enthalpy [$h = u + p/\rho$] (J/kg)

p pressure (Pa)

p_i interfacial pressure $p_i = p\alpha(1-\alpha)$ (Pa)

Q_{ij} interf.-liq./gas heat transf. per vol. rate (W/m^3)

t time (s)

u_i specific internal energy (J/kg)

v_i velocity (m/s)

v_r relative velocity ($v_r = v_g - v_f$) (m/s)

w pipe velocity in flow direction (m/s)

x spatial coordinate (m)

Γ_g vapor generation rate (kg/m^3)

α vapor void fraction

ρ_i density (kg/m^3)

ϑ pipe inclination

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