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Experimental and theoretical study of steam condensation induced water hammer phenomena

Imre Ferenc Barna*, Attila Rikárd Imre, Gábor Baranyai, György Ézsöl

Atomic Energy Research Institute (AEKI) of the Hungarian Academy of Sciences, Thermo-hydraulic Department, P.O. Box 49, H-1525 Budapest, EU, Hungary

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ABSTRACT

We investigate the steam condensation induced water hammer (CIWH) phenomena and present experimental and theoretical results. The experiments were performed in the PMK-2 facility, which is a full-pressure thermo-hydraulic model of the primary loop of the VVER-440/312 type nuclear power plant and located in the Atomic Energy Research Institute Budapest, Hungary.

The present experimental setup is capable to measure CIWH phenomena in a wide range of steam pressure, cold water temperature and mass flow rate at a high level of accuracy. On the theoretical side CIWH 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. Our study clearly shows that Relap5 and Cathare which are used in the nuclear industry to simulate nuclear power plant accidents cannot resolve the narrow pressure peaks created during a CIWH event. Only WAHA3 can model CIWH properly. Experimentally measured and theoretically calculated pressure peaks are in good agreement, however simulations always show additional pressure peaks. As a new feature in this study we present calculations without additional unphysical reflections caused by boundary conditions.

1. 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 deformation or pipe breakage. Such an unplanned transient is the CIWM. In thermal loops of atomic reactors or in other pipelines where water steam and cold water can mix, quick and dangerous transients can happen causing pressure surges which mean high financial expenses or even cost human lives.

In the following we will introduce the PMK-2 facility which is an integral experimental device and capable to produce CIWH effects (Szabados et al., 2007). On the other side we present the WAHA3 (Tiselj et al., 2004) model we use, which is a complex physical model suitable to simulate various quick transients in single and two-phase flows, such as ideal gas Riemann problem, critical flow of ideal gas in convergent–divergent nozzle, rapid depressurization of hot liquid from horizontal pipes (Tiselj et al., 2004) and column separation water hammer or even CIWH.

In the last two decades the nuclear industry developed a few complex two-phase flow-codes like RELAP5 (Carlson et al., 2003), TRAC (TRAC-PF1/MOD1, 1986) or CATHARE (Bestion and Geffraye, 2002) which are feasible to solve safety analysis of nuclear reactors and model complicated two-phase flow transients.

The model, WAHA3 (Tiselj and Petelin, 1997) has some similarities with Relap5. This means that the conservation equations are the same but the applied correlations are partially different (Tiselj and Petelin, 1997). 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. WAHA3, however is capable of capturing shock waves and describe pressure waves which may propagate quicker than the local speed of sound. As a second point WAHA3 has a quick condensation model which is not available for RELAP5 and CATHARE.

To our knowledge WAHA3 is the only model which is capable to simulate CIWH phenomena.

There is only one theoretical study from Chun and Hu (2000) that gives analytic formulas for the lower and upper critical feed-water flow rates that produces CIWH for a given effective pipe length.

The column separation induced water hammer can be properly calculated with RELAP5, ATHLET (Gesellschaft für Anlagen- und Reaktorsicherheit mbH, 2003) or with a recent model DYVRO (Thorsten et al., 2008). These models (together with our) can

* Corresponding author. Tel.: +36 1 392 2222/1472; fax: +36 1 395 9293.
E-mail address: barnai@aeki.kfki.hu (I.F. Barna).

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successfully describe the Simpson's experiment or other tests (Thorsten et al., 2008) as well.

In Section 4 we will mention our effort to simulate CIWH with RELAP5 and CATHARE, unfortunately in vain. These two large system codes have different numerical procedure which is unable to reproduce large and narrow pressure peaks in problems where long pipe length is combined with sonic velocity.

According to our knowledge, which is based on the study of the RELAP5 and CATHARE manuals there are no systematic study about CIWH phenomena with these codes.

In our following study we are going to present calculations concerning the amplitude and duration of the pressure peak generated by CIWH. The calculation of other quantities like void fraction and local temperatures are neglected, because these quantities cannot be measured properly and their calculated values are strongly model-dependent, while the pressure peak can be measured with high accuracy.

The main new message of the following study is to show how to eliminate the effects of unwanted and unphysical pressure peaks which are reflected from wall boundary.

2. Experimental setup

The WAHA experimental test section is well equipped with advanced two-phase flow instrumentation (wire mesh sensor, needle probes, fast pressure transducers and strain gauges). The mentioned instruments allow observations and studies about the dynamics of liquid and steam flow and liquid slug formation which is responsible for water hammer. The most advanced measuring instruments is the wire mesh sensor that consists of two grids of 12×12 parallel electrode rods placed into the flow in a short distance behind each other. The output information of the mesh sensor is the two-dimensional cross-section distribution of the void fraction with time resolution of 1 ms. A large set of data for 35 experimental runs performed (Prasser et al., 2008) with different initial conditions (pressure, liquid temperature, sub-cooling and intake flooding water flow rate). Two very interesting conclusions were made after the experiments. The first is that the CIWH has a highly stochastic nature this was confirmed with two consecutive experiments performed with equal initial conditions. In the first experiment a 100 bar pressure peak was formed and in the later experiment a 210 bar peak was measured. This can be explained by the stochastic nature of nucleation phenomenon in metastable systems; in this particular case it is droplet nucleation in under-cooled – and therefore metastable – steam (Debenedetti, 1996).

The second conclusion is that the amplitude of the first pressure peak showed a tendency to decrease with growing initial system pressure. In the following we will analyse the experiment labeled with E05.

The time history of the performed experiments are the following initially the pipe is filled with saturated steam. The transient begins when the sub-cooled water starts to flow into the pipe with a constant mass flow rate. At the first time of the transient the flow is purely stratified. As the flow continues and the inter surface is increased a well defined water level the Kelvin–Helmholtz instability occurs, which interrupts the stratification. Finally a cold water slug is formed capturing a steam bubble. A strong water hammer sounds when the whole steam pocket (a giant bubble) is condensed.

3. Theory

There are large number of different two-phase flow models with different levels of complexity (Stewart and Wendroff, 1984; Menikoff and Plohr, 1989) 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:

$$\frac{\partial A(1-\alpha)\rho_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l(v_l - w)}{\partial x} = -A\Gamma_g \quad (1)$$

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

$$\frac{\partial A(1-\alpha)\rho_l v_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w)}{\partial x} + A(1-\alpha)\frac{\partial p}{\partial x} - A\cdot CVM - Ap_i\frac{\partial \alpha}{\partial x} = AC_i|v_r|v_r - A\Gamma_g v_l + A(1-\alpha)\rho_l \cos\vartheta - AF_{l,wall} \quad (3)$$

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

$$\frac{\partial A(1-\alpha)\rho_l e_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l e_l(v_l - w)}{\partial x} + p\frac{\partial A(1-\alpha)}{\partial t} + \frac{\partial A(1-\alpha)p(v_l - w)}{\partial x} = AQ_{il} - A\Gamma_g\left(h_l + \frac{v_l^2}{2}\right) + A(1-\alpha)\rho_l v_l g\cos\vartheta \quad (5)$$

$$\frac{\partial A\alpha\rho_g e_g}{\partial t} + \frac{\partial A\alpha\rho_g e_g(v_g - w)}{\partial x} + p\frac{\partial A\alpha}{\partial t} + \frac{\partial A\alpha p(v_g - w)}{\partial x} = AQ_{ig} + A\Gamma_g\left(h_g + \frac{v_g^2}{2}\right) + A\alpha\rho_g v_g g\cos\vartheta \quad (6)$$

Index l 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 the 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. The uncertainties of steady-state correlations in fast transients are very high.

A detailed analysis of the source terms can be found in Tiselj et al. (2004) and Tiselj and Petelin (1997).

Two additional equation of states(eos) are needed to close the system of Eqs. (1)–(6). Here the subscript k can have two values 'l' for liquid phase, and 'g' for gas phase

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

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 (Seynhaeve, 1984).

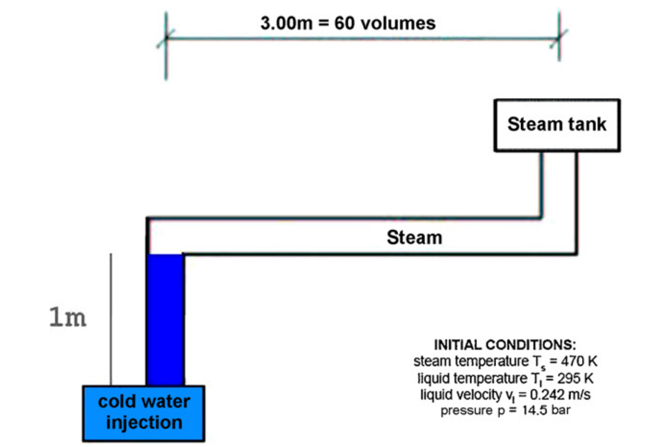

Fig. 1. The geometrical model with the initial conditions of the WAHA experiment.

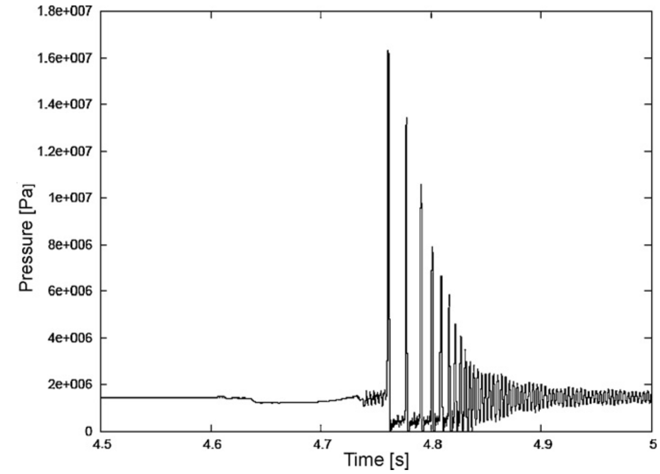

Fig. 2. Unphysical pressure peaks from boundary reflections in calculations.

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

$$\underline{\underline{A}}\frac{\partial\overline{\Psi}}{\partial t}+\underline{\underline{B}}\frac{\partial\overline{\Psi}}{\partial x}=\overline{S} \quad (8)$$

where $\overline{\Psi}$ represents a vector of the non-conservative variables $\overline{\Psi}(p, \alpha, v_l, v_g, u_l, u_g)$ and $\underline{\underline{A}}, \underline{\underline{B}}$ are 6-times–6 matrices and $\overline{S}$ is the source vector of non-differential terms. These three terms can be obtained from Eqs. (1)–(6) with some algebraic manipulation.

In this case the system eigenvalues which represent wave propagation velocities are given by the determinant $\det(\underline{\underline{A}} - \lambda\underline{\underline{B}})$. 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 the work of LeVeque (1992).

4. Results and discussion

Fig. 1 presents the geometrical model with the initial and boundary conditions of the experimental setup. The temperature of the saturated steam is $T = 470$ K with an initial pressure of $p = 14.5$ bar and the temperature of the cold water is $T_w = 295$ K with a flow velocity of $v = 0.242$ m/s. The horizontal length of the pipe is 3 m with a diameter of 7.3 cm. For a satisfactory convergence in the calculations we used 60 nodal volume elements for the horizontal pipeline. Second order numerical scheme was used with the MINMOD flux limiter (Tiselj et al., 2004; Tiselj and Petelin, 1997).

The Courant number which measures the relative wave propagation speeds of the exact solution and the numerical solution was set to CFL = 0.6 during the calculation.

It is possible to take into account the pipe elasticity in the model, if the Young's modulus is taken as 10^{10} N/m^2 (which is usual for steel) than the CIWH pressure peak is changed with less than 10 percent. This is a negligible effect among other uncertainties as we will see.

It is worth to mention that all kinds of correlations (heat, mass, impulse transfer) in both (dispersed and horizontally stratified) flow regimes have to be used during the simulation to get reasonable pressure peaks.

There is a 1 m long vertical pipe connected to the left end of the horizontal pipe. A pump was fixed to the free end of this pipe as the cold water injector. In the numerical simulation the pump represents a constant pressure boundary condition. The right side of the horizontal pipe ends up in an elbow pipe connected to a steam tank.

In the mathematical model a tank always represents a constant pressure boundary condition. Beginning of the calculation the left side vertical pipe is fully filled with water, the transient begins when the sub-cooled water starts to flow into the pipe with a constant mass flow rate. The flow is purely stratified in the first part of the transient. However, as the flow continues and the water level increases, which means about 60 percent steam void fraction, a Kelvin–Helmholtz instability occurs, which interrupts the stratification. Finally a cold water slug is formed which captures a steam bubble. A thunder-like strong water hammer sounds when the whole bubble is condensed. The measured widths of the pressure peaks are about 2 ms which is approximately one tenth of a human eye glance. It is worth to mention that our numerical simulations are capable to achieve such time resolution and the calculated pressure peak widths are in good agreement with measurements.

After the condensation of the steam bubble quick pressure waves start to propagate in the water towards the cold water injection pump, which acts like a closed pipe end causing total reflection. This reflected wave propagates to the right till it reaches the water steam phase discontinuity which lies approximately in the middle of the horizontal pipe. According to the high pressure wave propagation velocity in water and the short distance these kinds of reflections happen in some milliseconds after the main water hammer event. The two-phase flow Eqs. (1)–(6) contains no direct viscosity terms (the Euler and not the Navier–Stokes equations are solved) however on the right hand side of the energy equations there are water and wall friction terms which causes damping. If the length of the water-filled vertical pipe is enhanced the amplitude of the reflected waves can be suppressed. Former steam condensation induced water hammer simulations (Tiselj et al., 2004; Tiselj and Petelin, 1997) did not realize this role of the left side vertical feed-pipe and caused large number of unwanted pressure peaks.

If the length of the water-filled feed-pipe is changed from 1 m to 25 cm than a long train of decaying pressure peaks will appear in the calculations. Fig. 2 shows such pressure peaks.

Careful analysis of the vapor void fraction around 4.8 s showed no periodic oscillations (no boiling and no condensation) which means that the pressure peaks cannot come from cavitation.

We emphasize that we do not eliminate reflected waves with mathematical or physical means. We just force them to propagate and decay. It is possible and very simple to include absorbing (non-reflecting) boundaries into our model, however such conditions are questionable. It is practically impossible in our experiment to measure the ratios among incoming, reflected and absorbed wave

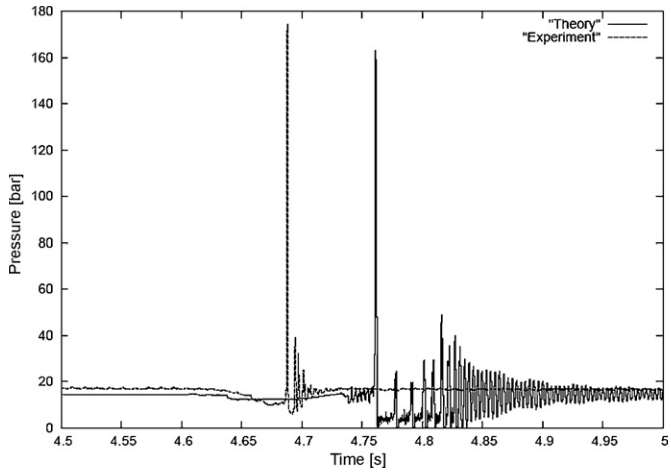

Fig. 3. Time history of the pressure peaks at 40 cm from the left end of the horizontal pipe.

amplitudes. Such experiments could be useful and would help us to develop realistic boundary conditions in numerical models.

Fig. 3 presents our calculated pressure peak according to the geometry of Fig. 1 and compares it with the measured data. Calculation and measurement were performed in the horizontal pipe at 40 cm from the left elbow. Experimental and theoretical pressure peaks are in good agreement. The time shift between the peaks has very little importance and it can be neglected because in engineering problems the existence and the absolute magnitude of the pressure peak have the crucial importance.

A key issue in such investigation is the question of numerical uncertainties. Our experience shows that pressure peaks are sensitive to the choice of the applied limiter (e.g. MINMOD or Superbee). The original WAHA3 model includes 3 different flux limiters, we tried additional ten cases. All the results are different; the major deviation is about 50 percent at the maximal peak pressure values. This means that steam condensation induced water hammer is a highly non-linear physical phenomenon with hard numerical consequences and have to be handled with great care.

Further and even larger uncertainties may come from the applied correlations, the condensation model and from the equation of state. The two-phase steam table, which is basically the numerical equation of state(eos) is taken from ordinary thermodynamics which is based on thermal equilibrium. However, during a quick transient like CIWH the fluid is not in equilibrium. How to develop eos for non-equilibrium systems is probably the largest unsolved dilemma of high-speed high-temperature hydrodynamics.

Our final statement is that recent numerical models and analysis can forecast if a CIWH event happens in a flow system with great confidence, but the absolute value of the overpressure peak needs further peculiar investigation.

As additional investigation we tried to simulate CIWH with RELAP5 and CATHARE as well. In the RELAP5 calculations nodalisation, initial and boundary conditions were the same as in WAHA3. Unfortunately, we cannot get any reasonable pressure peaks at about 4–6 s after starting. We tried different time steps and slightly modified the other parameters and performed about 10 different calculations. We can surely state, that a $\Delta t = 10^{-4}$ s step size gives maximal pressure peaks of about 2–3 bars at 2–3 s after the start which cannot be interpreted as a steam condensation induced water hammer pressure peak (being too small). Smaller, $\Delta t = 10^{-5}$ s time steps gives max. 3–4 bar peaks at about 1–2 s after the start. The void fraction history along the pipe is also a flat function and also cannot show any kind of 'bubble capture and collapse mechanism' which is the crucial reason of a CIWH event.

We also performed calculations with the CATHARE code. Nodalisation, initial and boundary conditions were the same here as well. The results are even worse, the maximal pressure peak is about half bar at $t = 8.5$ s after the start. There was no "bubble capture" mechanism seen in the void history.

We checked the users guide of CATHARE and found that Sierre and Bestion (2001) studied the column separation induced water hammer with CATHARE but no experience was made with the CIWH.

We also studied the RELAP5 manual (Carlson et al., 2003) and found in Volume 1 on Page 6 that the authors had a private discussion ended with the statement that RELAP5 is not capable to handle long pipe length combined with sonic velocity. So these two system codes are unable to calculate steam condensation induced water hammer at all.

5. Conclusions and outlook

We presented the Hungarian PMK-2 experimental facility which 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.

With the help of a one-dimensional two-phase flow model we investigated the CIWH phenomena. With a detailed analysis of the pressure wave propagation and the dynamics of the vapor void fraction along the pipeline the "steam bubble collapse" mechanism is identified which is responsible for CIWH in horizontal pipes.Our experimental and theoretical investigation confirm the following six conditions of Griffith (1997) which have to be fulfilled to produce CIWH events:

(1) The pipe must be almost horizontal (max. pipe inclination must be less than 5°).
(2) The sub-cooling must be greater than 20 °C.
(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 atm.

Experimentally measured and theoretically calculated pressure peaks are in good agreement.

As outlook we mention that construction of a new WAHA experimental facility is in progress in the Hungarian PMK-2 integral experimental device right now. The geometry is basically the same as mentioned above but a much larger horizontal pipe will be raised with 5 m 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, theoretical analysis show that appearance of 350 bar overpressure peaks are not impossible. We explain such huge discrepancies with the fact that CIWH events are very sensitive to initial flooding water velocity. The new experimental system has another peculiarity, two or even three independent CIWH events happen one after another separated by 10 s 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 m long former was only 3) there is enough room for two steam bubble formation. Unfortunately, the second steam bubble is "only formed" and shows a "nervous" shiver motion but cannot vehemently condense in our simulations. We think that the condensation model included in WAHA3 should be improved to overcome this problem.

Further theoretical investigations are in progress to clarify all details.

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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}	interfacial liquid/gas heat transfer per volume 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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