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## Modeling two-phase flow in pipe of the solar collector

**Abstract.** Solar collector is often used as evaporator in heat pump system. In the solar collector pipe, liquid is transferred from liquid phase to gas phase. The effective operation of heat pump depends on boiling point of the refrigerant and the process of phase change. Therefore, simulation of two-phase flow in the pipe is considered.

In two-phase flow, velocity field and pressure of the liquid phase are characterized by incompressible Navier-Stokes equation and compressible Navier-Stokes equation in the vapor phase. Dynamics of two-phase flow is described by Cahn-Hilliard equation to take into account the phase transition. Two-phase flow is solved using finite elements in COMSOL Multiphysics program using phase-field model based on Cahn-Hilliard phase variable equation. The higher the liquid density, the higher the Archimedes force on the vapor, which is the prerequisite for rapid and intense rise from the vapor bubbles. This also explains why the value of oscillation is bigger.

This article discusses the two-phase flow of solar collector coolant. Therefore, it is desirable to select the density value so that the liquid is rapidly steamed and fast, i.e., it has low oscillation. Based on these results, we can describe the effect of the liquid phase (density) on phase transitions.

**Key words:** two-phase flow, phase field, phase variable, refrigerant, heat pump.

### Introduction

Heat pump is a device that converts low temperature heat to the consumer in a highly potentially heat state. The functioning of the heat pump is based on the phenomenon of fluid-gas exchange. In this process, liquid evaporation absorbs heat and, conversely, condensed heat is released. At present the solar collector is often used as the evaporator in the heat pump system.

From effect of the solar energy, in the pipe of the solar collector refrigerant switches from the liquid phase to the gas phase. The effective operation of the heat pump depends on the refrigerant boiling point and the phase transformation process. Therefore, let's consider fluid in the pipe, the two-phase flow, when heat flow influences to the pipe from outside.

The two phase phase is classified according to the distribution of the vapor phase. The same classification that occurs in the pipe is referred to as flow regimes (Figure 1). Depending on the flow regimes, the fluid properties (hydrodynamic conditions) around the heated pipe wall change. For example, during friction loss of pressure or change of boiling process and change of heat exchange [1].
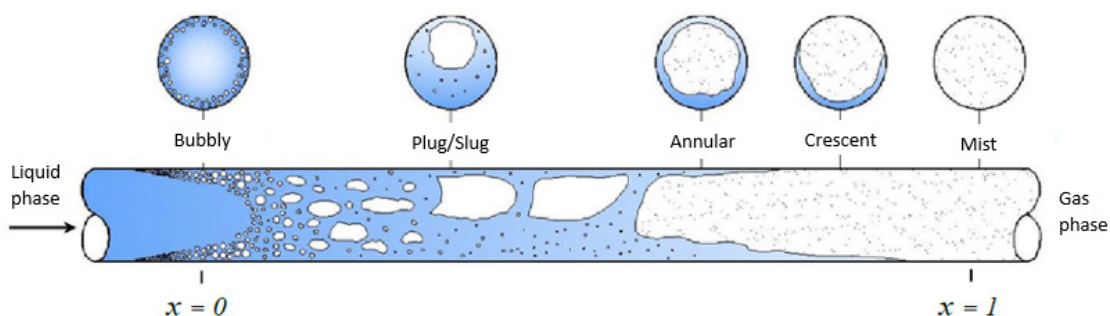
**Figure 1** – Scheme of two-phase flow modes in horizontal pipe

One of the most important goals of two-phase flow research is to determine the characteristics of heat exchange and pressure loss. In general, calculation of two-phase flow with loss of heat is a difficult CFD (thermohydrodynamic) calculation. On the one hand, the heat exchange leads to phase transitions, and consequently leads to the phase distribution and the flow regime. On the other hand, changes in the fluid dynamics characteristics, such as the pressure loss on the flow path, affect the heat exchange. At the same time, a single-component two-phase flow in the vertical or horizontal pipe will never be completely adjusted [2].

Boiling regimes (nucleate, transition, film) change depending on the amount of excess temperature and heat which transfer from the solid surface (Fig. 2). Here, the excess temperature is the difference between the solid surface temperature and the liquid's saturation temperature.
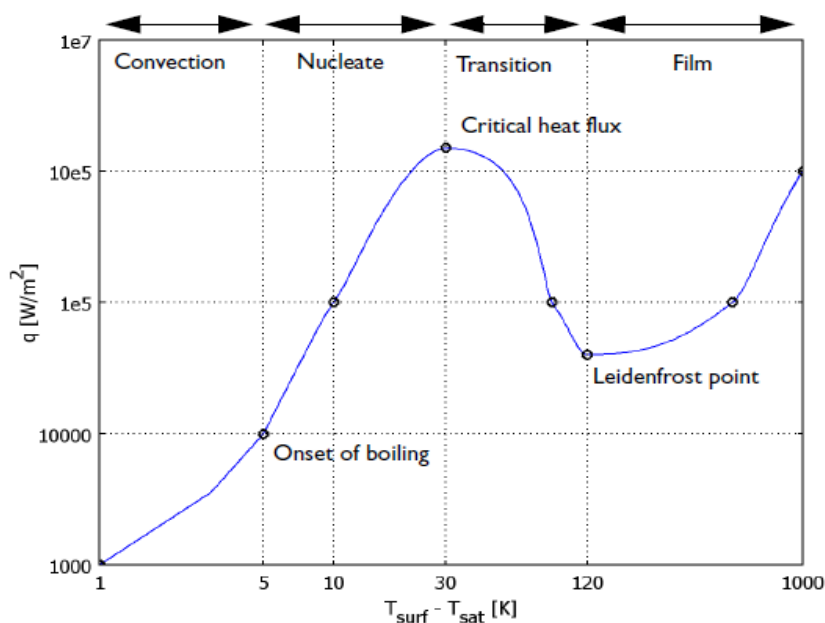


**Figure 2** – Boiling point of water at atmospheric pressure (101325 Pa).
Depending on the boiling point temperature and excess temperature

**Theoretical part**

*2.1 Mathematical model*
The physical phenomenon of the boiling fluid is determined by the interface dynamics. The boiling model uses the Navier-Stokes equation, the convection and the condensation equation. First, the boiling process is formulated by equations and boundary conditions. Then, to solve the problem, several approximations are made for characterize

interface, and solved by phase field equations [3]-[4].

In general, for the two-phase flow, the velocity field and pressure of the liquid phase are characterized by incompressible Navier-Stokes and continuity equation and the gas phase are characterized by compressible Navier-Stokes equation.

Since the liquid temperature is constant (saturation temperature) of all sizes, there is no need to solve the heat equation for liquid. The heat transfer equation is solved only for the gas phase.

It is difficult to set boundary conditions for the boiling process model.

The boundary condition for gas phase boundary:

$$\boldsymbol{n} \cdot \rho_V \boldsymbol{u_V} = \dot{m}\left(1 - \frac{\rho_V}{\rho_L}\right) + (\boldsymbol{n} \cdot \rho_{V}\boldsymbol{u_L}), \quad (1)$$

here, $\dot{m}$ − evaporation rate (mass flow through the liquid-vapor boundary) (kg/m$^2$·c).

In (1) equation, when density of the liquid doesn't equal to the gas density, the first expression of the right side gives us flow velosity which directed perpendicularly to the border.

For fluid, effects 3 different forces on the boundary. Therefore, boundary condition for liquid is:

$$\boldsymbol{n} \cdot [-p_L\mathbf{I} + \mu_L(\nabla\boldsymbol{u_L} + (\nabla\boldsymbol{u_L})^T)] = \dot{m}(\boldsymbol{u_L} - \boldsymbol{u_V}) + \sigma\kappa\boldsymbol{n} +$$

$$+ \boldsymbol{n} \cdot \left[-p_V\mathbf{I} + \mu_V(\nabla\boldsymbol{u_V} + (\nabla\boldsymbol{u_V})^T) - \frac{2}{3}\mu_V(\nabla \cdot \boldsymbol{u}_{V})\mathbf{I}\right]. \tag{2}$$

(2) is the balance of power that affects the interface. The second expression on the right describes the surface tension, and the last expression describes the total force of the pressure and viscous forces which influence from gas to liquid.

At the liquid-gas boundary (in energy equation), the temperature of the boiling point is taken as the temperature. Saturation temperature can be a function of pressure:

$$T = T_{sat}(p). \tag{3}$$

Thus, we can describe the mass flow in the phase boundary through the heat flow:

$$\dot{m} = -\left(\frac{M_w}{\Delta H_{Vl}}\right)\boldsymbol{n} \cdot \kappa_{V}\nabla T_V, \tag{4}$$

here:

$M_w$ − molecular mass of the gas (kg/mole),
$\Delta H_{Vl}$ − evaporation enthalpy (J/mole),
$T_{sat}$ − saturation temperature of the liquid.
This approximation ignores the work of kinetic energy and viscous forces [3].

Navier-Stokes and continuty equation for the liquid phase, compressible Navier-Stokes and heat transfer equation for gas phase (1) - (3) can fully describe the boiling process with boundary conditions. Finally, these equations can be solved by the free Lagrange-Euler's equation in Comsol program. But in this case we can not see the topological changes [5]-[6]. By making several necessary assumptions, we can solve this problem in a fixed grid using Phase Field.

*2.2 Phase Field model*
When switching to a fixed grid you have to make some approximations.

The dynamics of the two-phase flow is characterized by the Cahn-Hilliard equation. As noting in [4], [7], in order to take into account phase transitions, the equation for the phase field variable is introduced:

$$\frac{\partial \varphi}{\partial t} + \boldsymbol{u} \cdot \nabla\varphi - \dot{m}\delta\left(\frac{V_{f,V}}{\rho_V} + \frac{V_{f,L}}{\rho_L}\right) = \nabla \cdot \frac{\gamma\lambda}{\varepsilon^2}\nabla\psi \tag{5}$$

here:
$\varphi$ − dimensionless phase field variable (phase indecator), $|\varphi| \leq 1$,
$V_{f,V}$ − volume of the gas phase,
$V_{f,L}$ − volume of the liquid phase,
$\lambda$ − mixing energy density (H) ,
$\varepsilon$ − capillary width (in accordance with the thickness of the border) (m).

The parameters $\lambda$ and $\varepsilon$ have connection with the surface tension coefficient as follows:

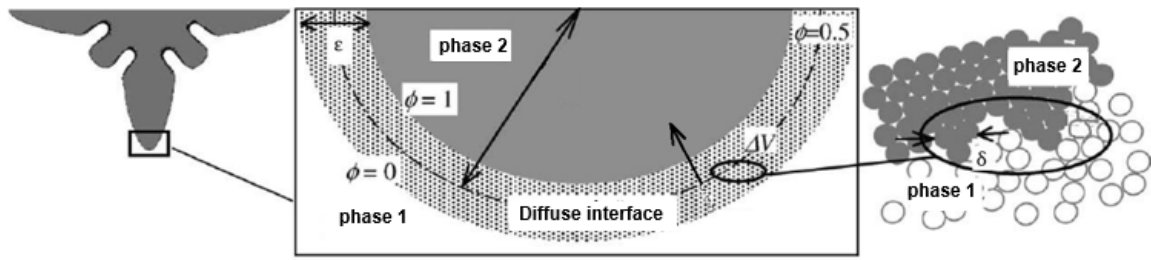$$\sigma = \frac{2\sqrt{2}}{3}\frac{\lambda}{\varepsilon}, \tag{6}$$

**Figure 2** – Phase field model

$\gamma$ – mobility, m$^3$·s/kg.

$\psi$ − auxiliary variable is determined by the equation:

$$\psi = -\nabla \cdot \varepsilon^2 \nabla\varphi + (\varphi^2 - 1)\varphi, \qquad (7)$$

$\delta$ (1/m) – smoothness of the surface (curvature) between the two phases (Figure 3). This variable is defined in the phase field model as follows:

$$\delta = 6V_f(1 - V_f)\frac{|\nabla\varphi|}{2} \qquad (8)$$

In the equation of motion the surface tension is taken into account along with volumetric forces (force of pressure, force of force and Archimedes force):

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} =$$
$$= \nabla \cdot [-p\mathbf{I} + \mu(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T)] +$$
$$+ \rho g + G\nabla\varphi \qquad (9)$$

here, $G$ – chemical potential (Pa):

$$G = \frac{\lambda}{\varepsilon^2} - \nabla \cdot \varepsilon^2 \nabla\varphi + (\varphi^2 - 1)\varphi. \qquad (10)$$

The density and viscosity of the medium are calculated as follows:

$$\rho = \rho_L + (\rho_V - \rho_L)\varphi, \qquad (11a)$$

$$\mu = \mu_L + (\mu_V - \mu_L)\varphi. \qquad (11b)$$

Indexes $L$, $v$ is represent the corresponding properties of liquids and gases. $\rho_V$ − gas density is determined by the equation of perfect gas (Clapeyron - Mendeleyev).

The continuity equation, as the liquid phase changes to the gas phase, is as follows:

$$\nabla \cdot \boldsymbol{u} = \dot{m}\delta\left(\frac{1}{\rho_V} - \frac{1}{\rho_L}\right). \qquad (12)$$

Now the question is to define an expression describing the rate of phase transformation. (4) can not be used because the threshold temperature gradient does not match the interface. In this case, the mass flow passing through the boundary surface is not estimated correctly. Instead, the following approximations are used to describe the mass flow:

$$\dot{m} = -\left(\frac{M_w}{\Delta H_{Vl}}\right)\boldsymbol{n} \cdot \kappa_V \nabla T_V \approx C\rho_L \frac{(T - T_{sat})}{T_{sat}} \qquad (13)$$

here, C – constant value (m/s).

Mass flow includes to the energy equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p(\boldsymbol{u} \cdot \nabla)T = \nabla \cdot \kappa\nabla T - \frac{\dot{m}\delta\Delta H_{Vl}}{M_w} \qquad (14)$$

The connection of equations (12) and (13) give reacing the temperature of the interface to saturation temperature.

Coefficients of thermal conductivity and heat capacity are calculated as the volume function of the two phases:

$$\kappa = (\kappa_L - \kappa_V)V_{f,L} + \kappa_V, \qquad (15a)$$

$$C_p = (C_{p,L} - C_{p,V})V_{f,L} + C_{p,V}. \qquad (15b)$$

**Modeling in COMSOL Multiphysics**

It is convenient to use COMSOL Multiphysics software package to simulate the process. Figure 4 shows the geometry and initial conditions required for the process. The heat flow is transferred to the copper wall. The amount of heat flux was obtained in a single amount of heat from solar radiation (about 1000 W/m$^2$); Refrigerants of various density are considered as liquid (the main is R-407C).
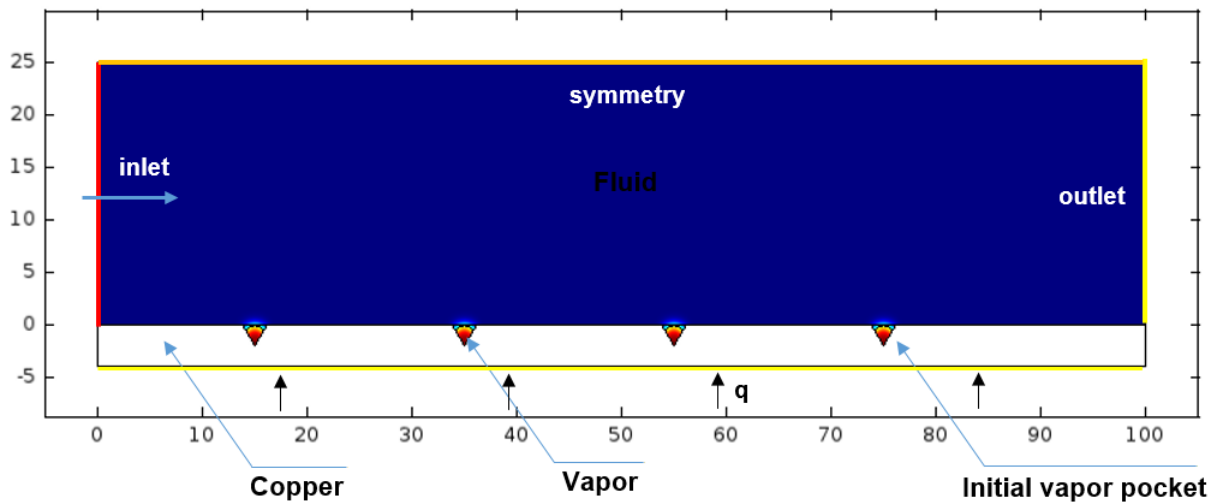
**Figure 4** – Geometry and initial conditions

Saturation temperature (R407C) is 229.4 K, external medium pressure is 101325 Pa. Liquid viscosity $0,158 \cdot 10^{-3}$ Pa. The density of gas is given by the law of the ideal gas, vapor viscosity $1,25 \cdot 10^{-5}$ Pa. The surface tension ratio is 0.0069 N/m. The copper primary temperature is 238 K, the density is 8700 kg/m$^3$, the thermal capacity is 385 J/(kg), the thermal conductivity is 400 W/(m·K). In the model (Fig. 5), the heat transfer is accompanied by solid-copper phase (zone 3) with the liquid-vapor phase.
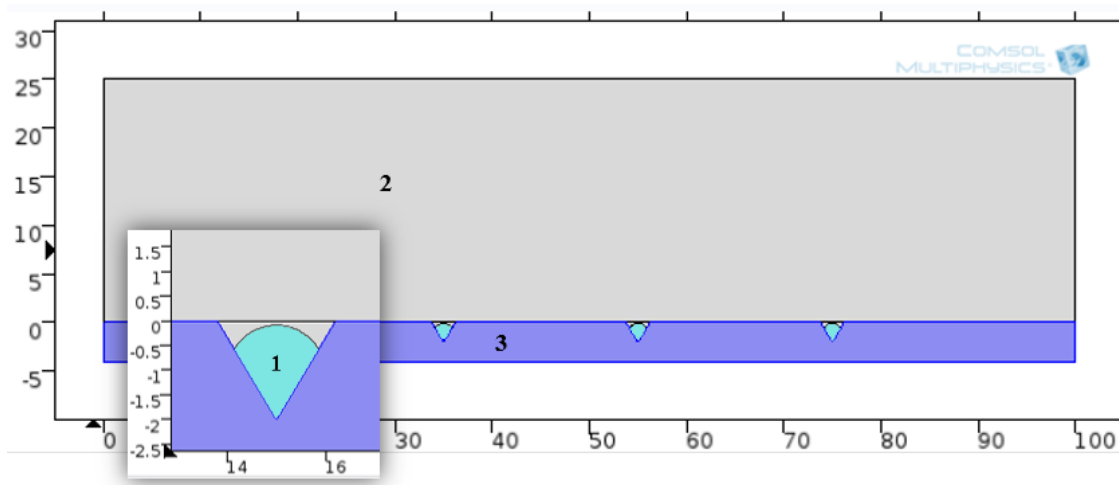


**Figure 5** – Model of the problem

Zone 1 is a vapor phase, zone 2 is liquid, and zone 3 is solid. Phase Field (Laminar Two-Phase Flow, Phase Field) and Heat Transfer In Fluids in the zone 2 are selected. The zone 3 is a physics of Heat Transfer in Solids in solid state. (5) - (15), which describes two-phase flows, are covered by the physics of Laminar Two-Phase Flow, Phase Field and Heat Transfer in Fluids.

**Results and Discussions**

COMSOL Multiphysics program solved the numerical model of two-phase flow in the pipe. Figure 6 shows the two-phase flow model of pipe refrigerant (R-407C) on the basis of the problem's geometry. The given heat is supplied to the fluid and vapor through the copper-liquid or copper-

vapor boundary by heating the copper and passing through the heat material. Due to the temperature increase, two-phase flows are formed on the pipe. The liquid density is 1136 kg/m³. Figure 6, e) and f) show that the pipe is a two-phase flow – annular regime (shown in Figure 1). The liquid phase is surrounded by a rim-like pipe wall, and most of the vapor phase is covered entirely by the pipe. And in a ring liquid layer, the vapor phase is found to be bubbles.
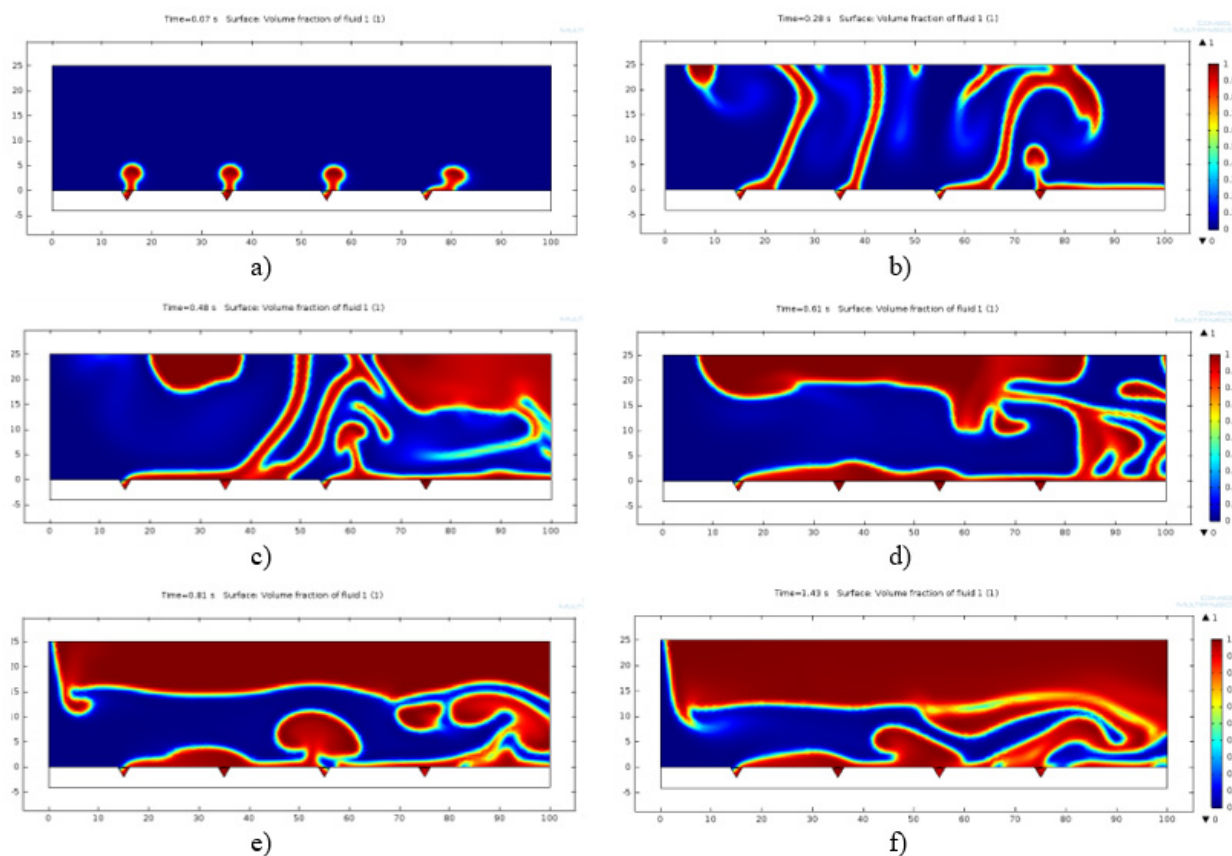


**Figure 6** – Two-phase flow (refrigerant R-407C)

Figure 6 shows t = 0.07 (a); 0.28 (b); 0.48 (c); 0.61 (d); 0.81 (e); 1,43 (f) seconds are displayed. The following sequence of flows is repeated e) and f).

a) bubbles appear and begin to rise. The bubble growth is directly related to the saturated vapor pressure, which acts as a response to the atmospheric and fluid's hydrostatic pressure, due to increased temperature. And, in addition, the growth of the mass due to the evaporation of the liquid in the vapor bubbles. From the difference in liquid and vapor density, i.e., Archimedes force bubbles rise high. The mushroom shape of the bubble form is due to a decrease in the effect of the low density fluid and the increase in the amount of the surface tension coefficient between the liquid and the vapor bubbles [2].

b) because of the high heat transfer from the surface, the bubbles can be intensively formed, raised, coupled to one another, or controlled by columns.

c) and d), it is possible to notice that the boiling mode is under construction. And so much of the vapor phase began to flow into the center of the pipe.

In the case of e) and f), the annular mode of two-phase flow is formed.

The following steps have been taken to show cooling of the working fluid. Because of the two-phase time-dependent, unstable process, the mean space and the time value of the phase space variation (taking into account that the phase variables are fluid, where $\varphi = 0$ is a fluid, $\varphi = 1$). First, the vertical axis of the pipe outlet has not been

reached at least 1 mm (Figure 7). This ensures that the impact of the boundary condition is minimal. By this straight line, the $\varphi$ - phase variable is derived from the averaged mean. Second, a graph between the average value and the time taken at each time space is constructed.



<center>a)</center>
<center>b)</center>
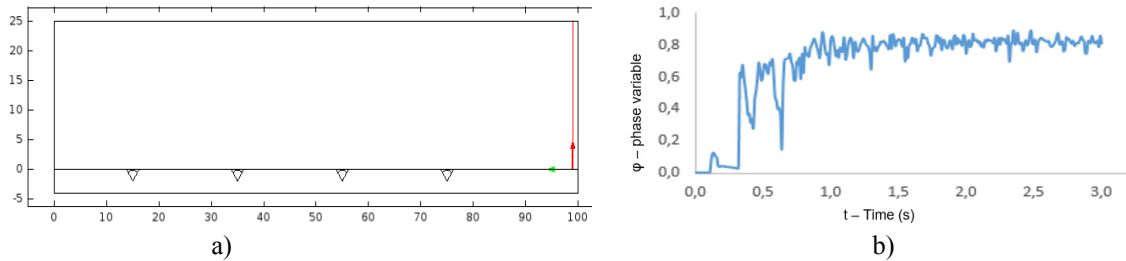
**Figure 7 –** Space averaging
a) space averaging line; b) time dependence of $\varphi$ – to the refrigerant R-407C.

As we can see from the Figure 7.b $\varphi$-$t$, where $\rho$ = 1136 kg/m$^3$ (refrigerant R-407C), the value of $\varphi$-phase is relative to $t$ = 1 second. This means that the circular flow mode has already been formed (Fig. 6, e), f) ). Taking this into account, the third is averaged over time since the relative stability of the phase variable.

When the density $\rho$ = 1136 kg/m$^3$, the mean of phase variables was $\varphi$ = 0.812. Oscillation (difference between maximal and minimum deviations) is 0.24.

Fourth, the three steps mentioned above have been repeated without changing their refrigerant density (only by density change).
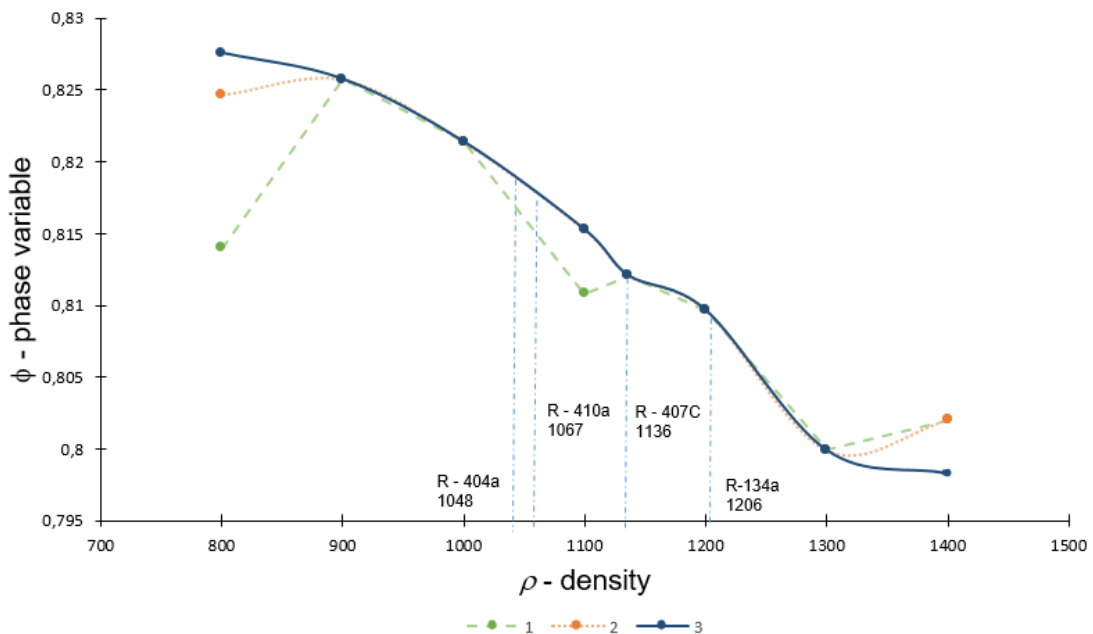


**Figure 8 –** Dependence of the $\varphi$ – variable on density

The relationship between the given density and the mean value of the corresponding phase variables is plotted (Fig. 8).

The results show that at low density levels, the fluid gas phase is higher, the phase oscillation is 0.11-0.2. But the gas phase is slowly moving. At high density values, the fluid is rapidly converted to gas, but the mean value of the phase variable is relatively low and oscillation is about 0.24 to 0.27.

The higher the liquid density, the higher the Archimedes force on the vapor, which is the prerequisite for rapid and intense rise from the vapor bubbles. This also explains why the value of oscillation is bigger.

This article discusses the two-phase flow of solar collector coolant. Therefore, it is desirable to select the density value so that the liquid is rapidly steamed and fast, i.e., it has low oscillation. Based on these results, we can describe the effect of the liquid phase (density) on phase transitions.

**Conclusion**

The two-phase flow was solved by means of the finite elements in COMSOL Multiphysics computer program using a phase field model based on the equation of phase variable of Chan-Hilliard. According to the problem, the two-phase flow of refrigerants at different densities was reviewed and compared. The phase variable for the refrigerant R-407C is 0.812, the oscillation is 0.24. For refrigerants with a density of 800-900 kg/m$^3$, this value was about 0.825-0.827, the oscillation was 0.15-0.21. For refrigerants with a density of 1300-1400 kg/m$^3$, the above values were 0.798-0.799 and fluctuations of 0.24-0.26.

By examining the results, the higher the liquid density, the more rapid phase changes were observed, but the phase of the vapor phase was small. Conversely, if the density is small, the volume of the vapor is high, but the phase exchange is slow.

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