Two-phase flow modeling of a vertical channel by Relap5 code system

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ABSTRACT

It is known, that the phenomena of phase change and the boiling crisis are not yet fully deciphered, which leads to the generation of technical problems, such as frequent breakdowns and accidental shutdowns in thermal installations. The main objective of this study is the numerical analysis of an ascending flow during boiling in a vertical channel by the Relap5/Mod3.2 code. This code can helps in the analysis heat transfer by convection, boiling, condensation and even by radiationin steady state or in transition regimes. The validation was made by comparing our results of simulationwith the experimental results under the same conditions (pressure, mass flow, diameter and flux density). This analysis allowed us to determine the different regimes of heat transfer along the channel, as well as the conditions of appearance of the boiling crisis.

I. Introduction

Boiling can cause, under certain conditions, a kind of blockage in the evacuation of heat, a consequence of a critical value of heat flux (CHF) (Liu et al., 2015). At the origin of the destruction of the boundary layer, this phenomenon is usually linked to a separation between the liquid and the heating wall by a film of vapor (Yeoh et al., 2005). The liquid contact area with the heating wall being reduced, the temperature of the latter consequently increases suddenly. This is referred to as a heat transfer crisis or boiling crisis (Dorochenko et al., 1995). Boiling is useful in industrial applications (Delhaye et al., 1981), as it promotes heat exchange processes, with the aim of achieving very high heat transfer coefficients and ideal operation of thermal machines (Payan et al., 2006). Nevertheless, there are critical phenomena such as boiling crisis which limit the safe operation of these facilities (Payan et al., 2006). These phase change phenomena and the boiling crisis are not yet mastered, and can cause the generation of technical problems such as frequent breakdowns and accidental shutdowns of thermal installations (Bergles et al., 1981 Hass et al., 2013). The use of computer codes such as Relap5/Mod3.2, helps in the thermal-hydraulic analysis of the complex phenomena of heat transfer by convection, boiling, condensation and even by radiation. The Relap5 code makes it possible to examine the axial evolution of the thermo-hydraulic parameters of the fluid in forced convection, and determines the boiling limits which separate the different flow regimes. The main objective of this study is the numerical analysis of an ascending flow during boiling in a vertical channel by the Relap5/Mod3.2 code. A qualitative and quantitative evaluation of our results was carried out by the real case study of water flow along a vertical channel heated uniformly in steady state. The validation of the results was made by comparing our simulation results obtained by the Relap5/Mod3.2 code with the experimental results of Bennett in the same experimental conditions (Pressure, flow mass, diameter, and heat flux) (Groeneveld et al., 2002).

II. Relap5 code presentation

RELAP5 is a system code developed at the Idaho National Engineering Laboratory (INEL) at the request of the United States Nuclear Regulatory Commission (NRC) (Relap, 1998). It is intended for the analysis of the transients of the various components of the Light Water Reactor (LWR). The use of this code include its application in the nuclear and non-nuclear fields (Deghal Cheridi et al., 2016, Serraro-Aguilera et al., 2017, Tuunanen et al., 2000). It was designed to simulate the thermal-hydraulic behavior of installations during accidental or incidental transient conditions. Relap5 is widely used in nuclear safety studies; the use of this code includes its application in the nuclear and non-nuclear fields (Deghal Cheridi et al., 2016; Serraro-Aguilera et al., 2017; Tuunanen et al., 2000) and its field of application extends to energy systems using water and steam. The research works carried out in this direction are very few and they are limited to the nuclear field. Relap5 is based on a non-homogeneous and non-equilibrium hydrodynamic model of a two-phase equations systemwhich is formulated in terms of temporarily averaged volumes and parameters of the flow. Phenomena that depend on transverse gradients, such as friction and heat transfer, are formulated in terms of bulk properties and employ empirical transfer coefficient formulations. In situations where the transverse gradients cannot be represented as empirical transfer coefficients (such as under saturated boiling), additional models are used (Relap, 1998; Deghal Cheridi et al., 2016; Serraro-Aguilera et al., 2017; Tuunanen et al., 2000). The system model is solved numerically with a semi-implicit finite-difference technique. This option is suitable for stationary calculations and for slow variations (quasi-stationary). Version 3 of the Relap5 code reflects increased knowledge and new simulation conditions from both small and large scale experiments, theoretical research in two-phase flow, numerical solution methods, programming advancement, and larger possibilities of computers (Relap, 1998).

Relap5 is formed from several modules using an ordered structure. Compositional models form the basis of thermal, hydraulic and neutron processing. Steady state related calculations use several algorithms for kinetics, control system, hydrodynamic and thermal transient. Transient calculation is characterized by the temporal variation of one or more variables related to each phenomenon. The transient regime must be preceded by a well-established permanent regime in which the initial conditions of the simulated accident are fulfilled. The initial values must be provided by the user as input for each component (Relap, 1998). The parameters such as pressure, flow rates and densities would adjust quickly, but thermal effects would change more slowly.

Relap5 code includes many generic component models for modeling various systems such as pipe, pump, turbines, separators, valves, accumulator, point kinetics of reactors, thermal structure, control system component, etc. (Relap, 1998). In addition, other special process models are introduced for different shape losses, flows in pipes with variable surfaces, branching and constricted flows, etc.

The code allows the calculation of the heat transfer through the solid walls, delimiting the hydrodynamic volume. The thermal structures are solid elements, generating heat or not, placed in contact with the volume of fluid. Each thermal structure is defined by the indices of the left and right control volumes, the solid volume, its thickness and the type of material. Modeling of heat transfer from metal structures typically includes fuel rods and plates (electrical or nuclear heat source), heat transfer through steam generator tubes, and heat transfer to pipe walls and reservoirs in the case of a reactor. The temperature distribution in thermal structures is represented by one-dimensional heat conduction in spherical, rectangular or cylindrical coordinates. Thermal conductivity and heat capacity can be simulated by a series of tabulated values as a function of temperature or of a given function. The integral form of the heat conduction equation is given by expression (1) (IAEA-NUREG/CR-5535).

$$\iiint_v \rho C_p(T,\bar{x})\frac{\partial T}{\partial t}(\bar{x},t)dV = \iint_s k(T,\bar{x})\bar{\nabla}T(\bar{x},t).d\bar{s} + \iiint_v S(\bar{x},t)\,dV \qquad (1)$$

The heat transfer model of the RELAP5 code divides the system into two phases, liquid and vapor. The total heat flux Q takes the following form [15]:

$$Q = h_s(T_w - T_{refr}) + h_l(T_w - T_{reff}) \qquad (2)$$

Where; hs: coefficient of heat transfer to steam,h_f : coefficient of heat transfer to liquid, T_w : wall temperature, T_{refr} : vapor reference temperature, and T_{reff} : liquid reference temperature.

III. Nodalization and simulation

The realization of hydrodynamic calculations is based on the concept of volumes and junctions.The purpose of this work being the numerical study of an ascending flow during boiling in a vertical channel by the Relap5/Mod3.2 code, the philosophy of use of the Relap5 code consists in subdividing the hydrodynamic system (fluid) into control volumes connected by flow junctions. The thermal behavior of the metal wall of the tube is simulated by heat structures connected to the hydrodynamic volumes. The thermal-hydraulic conditions at the channel inlet and outlet are imposed by components specific to the Relap5 code. These components are, Time-Dependent Volume to impose the temperature and the thermodynamic state of the fluid, Time-Dependent Junction, to impose the flow rate and single junction to impose the pressure. The geometric and thermal-hydraulic parameters used in this study for each case are presented in Table 1.

Table 1. Boundary conditions.

Experience	D (mm)	L (m)	P (MPa)	G (kg/m^2s)	Q (kW/m^2)
Test case 1	12.6	5.5	6.9	380	512
Test case 2	12.6	5.5	6.9	1953	1090
Test case 3	12.6	5.5	6.9	5181	1750

The nodalization scheme adopted in this work is shown in Figure 1. The flow channel (pipe) is subdivided into 32 control volumes, 31 junctions and 32 heat structures. The thermal-hydraulic conditions at the channel inlet are simulated by the TDJ-110 component connected with the TDV-100 component. Pressure is imposed at the channel outlet using the SJ-120 component connected with TDV-200.

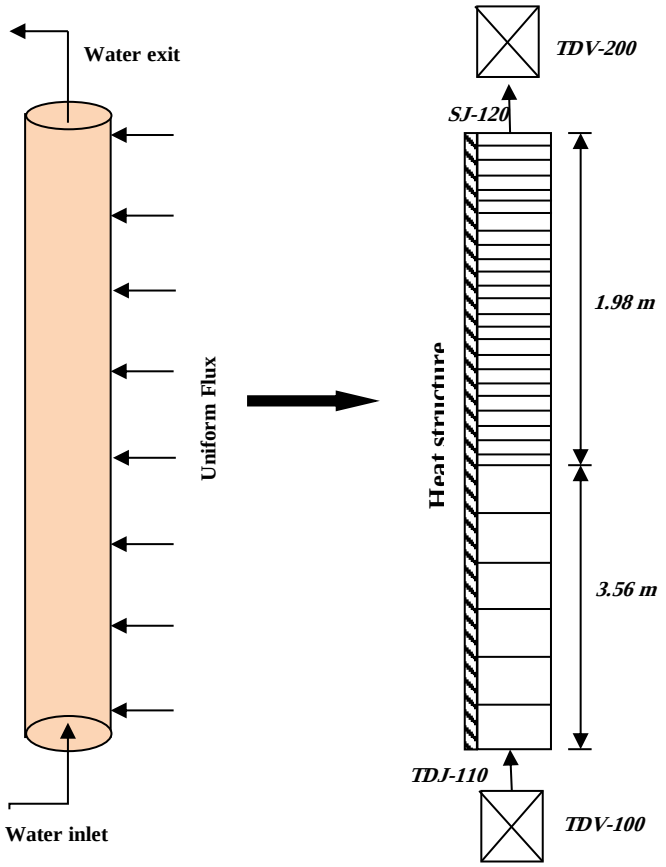

Figure 1. Channel nodalization by Relap5 code.

IV. Results and Discussions

The Relap5 system code was used to predict the establishment of the boiling crisis in a vertical channel. The theoretical results show the temperature variation of the channel wall as function of the thermodynamic title of flow. The boiling crisis position is distinguished by the rapid increase in wall temperature. Moreover, the boiling crisis point clearly defines the boundaries of each boiling regime (Pre-CHF and Post-CHF). The ascending flow of water inside the channel isdesigned to operate under the critical heat transfer conditions. For cooling purpose and to lead an overheating conditions, heat is supplied to the outer surfaces of the channels and removed from the inner surface by the water circulating inside. Therefore, all temperature along the channel must be taken into account because it is considered as a key parameter for safety analysis in industrial and nuclear installations under accidental conditions. We have chosen to compare our results with the experimental results of Bennett (Ling et al., 2018) under the same experimental conditions (pressure, mass flow, diameter and heat flow) for a vertical channel heated in uniformly.

The graphical comparison requires the representation on the same graphs of the results obtained by the Realp5 code and those resulting from the Bennett experiment and the simulation results of Ref [16]. These results concerns to plot the axial distribution of the internal wall temperature, the heat transfer coefficient, the void fraction, vapor and liquid velocities of the fluid along the vertical channel. The curves of Figures 2, 3, and 4 shows the wall temperatures of the vertical channel, which have the same shapes and the same asymptotic tendencies as the experimental results. The distribution of the fluid temperature inside the vertical channel is gradually heats from the inlet to the outlet. The variation of the wall temperature clearly expresses the various modes of heat transfer and furthermore predicts the exact position of the boiling crisis along the heated channel. It can be seen that our numerical results agree better with the experimental data than the prediction of Ref [16]. After simulation, we can conclude that the nucleate boiling regime is dominant. At 3.5 m in axial position, the temperature jump quickly to reach maximal high critical values of 1100, 850 and 800°K, respectively for the three cases, where the predicted CHF location of simulation coincides slightly with measurement. The calculated wall temperature is more than 50 °K lower than the experimental data. Initially, we can say that the increase in temperature is forced by convection heat exchange between the channel surface and the fluid. Moreover, the fluid temperature increases with the load rise. This rise in temperature is the result of vapor production increasing which induces the formation of a vapor layer that isolates the wall of the channel. Indeed, there is a drop in heat transfer between the water and inner wall of tube leading the establishment of the boiling crisis. Consequently, the material could be damaged by overheating, which causes cracks, leaks, thermal fatigue or creep failure.

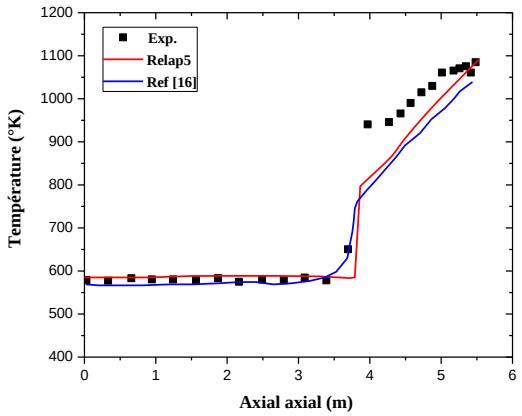

Figure 2. Wall temperature comparison between numerical results, experimental data and Ref [16] for test case 1.

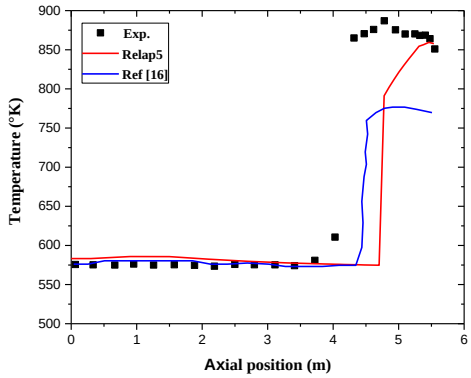

Figure 3. Wall temperature comparison between numerical results, experimentaldata and Ref [16] for test case 2.

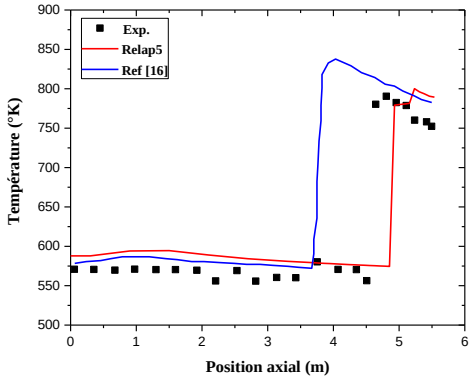

Figure 4. Wall temperature comparison between numerical results, experimentaldata and Ref [16] for test case 3.

The heat transfer inside the vertical channel is ensured by the nucleate boiling regime, which is characterized by a fluid-saturated temperature, temperature of internal wall and a good heat transfer coefficient. Figure 5 illustrates the void fraction variation along the channel length for the three loads. Initially, at the channel inlet, the void fraction increases with distance along the channel from 0 to 1 for all cases. After that, it is maintained until reaching the values of 0.9 (90%) for case 3, 0.98 (98%) for case 2 and 1 (100%) for case 1 at the end of the channel. As expected, this behavior expresses clearly the tendency of the void fraction to increase along the channels.

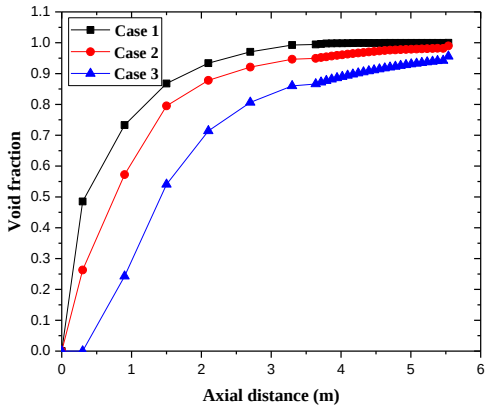

Figure 5. Void fraction comparison along the vertical channel between numerical results of Relap5 for all test cases.

Vapor and liquid temperature variations along the vertical channel are presented in the Figures 6 and 7. For the three cases, the vapor temperature is maintained constant, then start to increase at 4m for the first case,4.8m for the second case and 5.25 m for the third one, reaching a maximum value of 548 °C, 350°C and 27 °C, respectively at the outlet of the channel (Fig. 6). Concerning the liquid temperature variations, we can see that the temperature for all cases is less than the vapor temperature. The results show that the temperature increases with channel length, and then decreases slightly. The two regions (increase then decrease) are connected by a critical value, which represent the maximum (Fig. 7). It is evident that the vapor temperature is more significant than the liquid temperature.

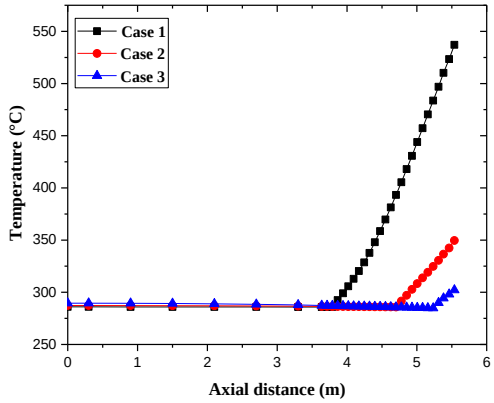

Figure 6. Vapor temperature comparison inside the vertical channe lbetween numerical results of Relap5 for all test cases.

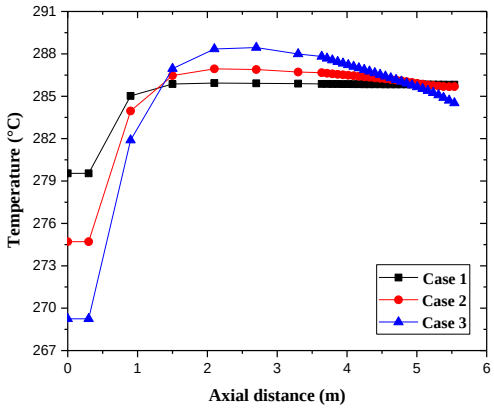

Figure 7. Water temperature comparison between numerical results of Relap5 for all test cases.

Vapor and liquid velocity variations along the vertical channel are presented in the Figures 8 and 9. The vapor and liquid velocities increase along the channel reaching 75 m/s, 50 m/s, and 20 m/s for vapor velocity, and 68 m/s, 45 m/s and 15 m/s for liquid velocity at the outlet of the vertical channel. After these results, we can conclude that the vapor velocity is more significant than the liquid velocity and the both curves of Figures 8 and 9 have the same trend. This conclusion indicate the magnitude of the mechanical disequilibrium between the vapor and liquid phases (Deghal Cheridi et al., 2013; Deghal Cheridi et al., 2019).

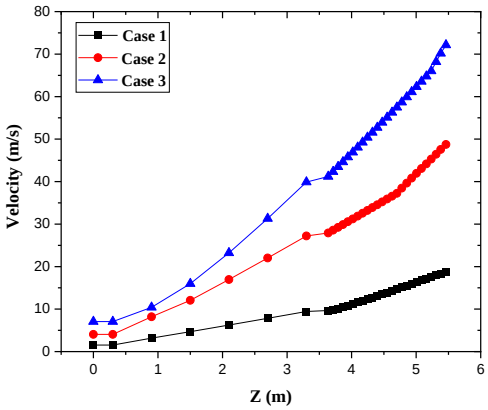

Figure 8. Vapor velocity comparison between numerical results of Relap5 for all test cases.

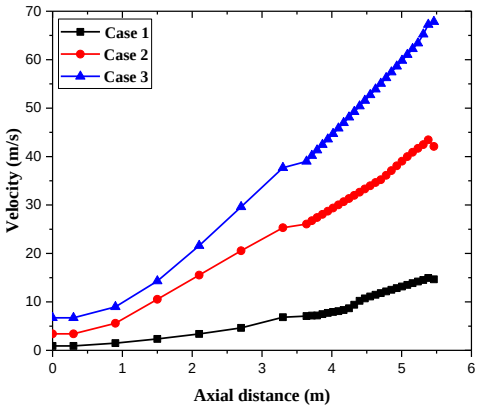

Figure 9. Water velocity comparison between numerical resultsof Relap5 for all test cases.

Figure 10 depicts the distribution of the heat transfer coefficient with height. Heat transfer coefficient in nucleate boiling region mainly depends on heat flux, thus, an increase in heat flux causes an increase in two phase boiling heat transfer coefficient (Yabuki and Nakabeppu, 2017), as illustrated in Figure 10. After a slight linear increase in heat transfer coefficient in the single-phase liquid region it drops until it reaches 170kW/m^{2}K, 95kW/m^{2}K and 58kW/m^{2}K for case 3, case 2, and case 1 respectively, then, it increases linearly again. The maximum values of the heat transfer coefficient have been observed at a height of 5.3 m of the vertical channel. After this, it can be understood that heat transfer coefficient can be different through channel length, which is due to bubble formation and departure, velocity and flow pattern (Deghal Cheridi et al., 2019). Indeed, we must also note the importance of the correlations used to estimate the convective heat transfer coefficient and the accuracy of the values of the physical properties used in the heat conduction calculation. These two factors significantly affect the calculation.

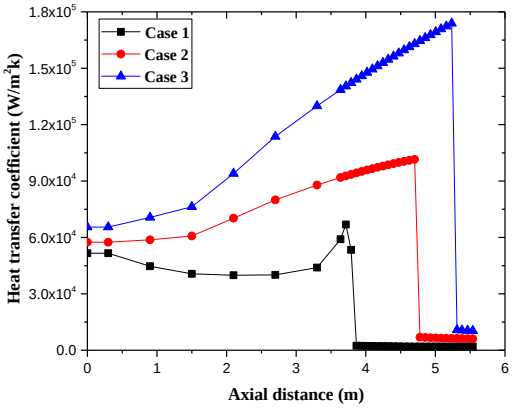

Figure 10. Heat transfer coefficient comparison between numerical results of Relap5 for all test cases.

V. Conclusion

The theoretical model of the RELAP5 code used evaluates the heat transfer conditions before, during and after the establishment of the Critical Heat Flux (CHF). It calculates the axial evolution of the thermo-hydraulic parameters of the fluid in forced convection, and determines the boiling limits which separate the different flow regimes. A qualitative and quantitative evaluation of our results was carried out by the study of real cases of water flow along a vertical channel heated in a uniform manner in steady state. The validation of our calculation model was made by comparing our results with those from experience. It appears that the results of the RELAP5 code agree satisfactorily with the experimental data in the nucleate boiling regime (or pre-CHF). The slight deviation recorded in the Post-CHF regime (at high titers) is explained by an inadequate choice of the RELAP5 code options for the dispersed flow regime. The obtained results within the framework of this study are of much more interest to industrial utilities for the production of steam and electrical energy. In addition, this study makes it possible to carry out the expertise operation correctly and to formulate recommendations for operators and designers of steam generators.

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