

Liquid Temperature Stratification in Piping of Nuclear Power Plants

J.L. Muñoz-Cobo, A. Escrivá, J.C. de la Rosa

Universidad Politécnica de Valencia, Spain.

Abstract. In this paper we present the main results of thermal stratification in pipes of Nuclear Power Plants obtained at the Polytechnic University of Valencia, using the commercial code CFX 5.4.1, and the structured mesh code TUBE-3D developed at the Polytechnic University of Valencia, solving in 3D, the mass, energy and momentum equations in conjunction with the k-ε turbulence equations. The code results have been compared with experimental data obtained from the thermocouples located in the pipes.

1. INTRODUCTION

Thermal stratification in pipes of NPP is an important issue for several reasons. The first one is that when temperature stratifies in the hot leg of PWRs, we can have thermal stresses that can affect the integrity of the primary system. The second reason is that errors in the fluid temperature given by the thermocouples can affect the mass-flow-rate measurements.

The thermal stratification is produced in horizontal pipes when we have a fluid at a given temperature, and we inject a fluid at different temperature and very low velocity. In this case, if the original fluid is colder, then, when the hotter fluid enters in the pipes the buoyancy force moves the fluid toward the upper part of the pipes, producing a thermal stratification in the pipes.

The thermal stratification can be predicted by 3D codes that solves the conservation equations

$$\frac{\partial(\rho\phi)}{\partial t} + \bar{\nabla}(\rho\phi\bar{v}) - \bar{\nabla}(\Gamma_{\phi} \cdot \bar{\nabla}\phi) = S_{\phi} \quad (1)$$

where

ϕ = conserved magnitude

ρ = density

\bar{v} = velocity vector

Γ_{ϕ} = diffusion coefficient

S_{ϕ} = source term

There exist many codes that solve the conservation equations with different boundary conditions.

The Polytechnic University of Valencia (UPV) has studied the liquid temperature stratification in pipes using commercial codes (like CFX) and developing new codes (like TUBO-3D).

In the section 2 of this paper we outline the work made at the UPV related with the use of commercial codes. The codes developed by UPV are outlined in the section 3.

2. STUDY OF THE LIQUID TEMPERATURE STRATIFICATION IN PIPES AT THE UPV WITH COMMERCIAL CODES

The Reactor Coolant Systems (RCS) hot leg temperature measurements are used in control and protection systems to ensure that the temperature is within design limits and in a surveillance procedure. The uncertainty of the measurements can have a significant impact on the Pressurized Water Reactor (PWR) performance. A precise measurement of the hot leg temperature is difficult due to the stratification, caused by the incomplete mixing of the coolant that leaves the fuel assemblies at different temperatures. The difference in the fuel assembly exit temperature, when operating at full power was normally no more than 30°C, with the lowest temperatures measured at the exit of peripheral assemblies. Flow from a fuel assembly in the centre of the core mixes with the coolant from nearby assemblies as it flows around the guide tubes and the support columns toward the hot legs nozzles. Flow from a fuel assembly on the peripheral has little opportunity to mix with hotter flows before reaching the nozzles, so a significant temperature gradient can exist at the hot leg [1] [2].

The UPV is studying the thermal stratification in the hot legs of a Pressurized Water Reactor (PWR). In Spain we have several PWR, and we are analyzing the coolant behaviour in the vessel upper plenum and hot legs of the NPP of Vandellós 2. This NPP is a 3000 MWth Westinghouse reactor with 3 hot legs and 157 fuel bundles [3].

To examine the piping stratification, we model the upper plenum with all the internal structures, i.e. the 52 guide tubes and 40 support columns.

To analyze the water behaviour inside the upper plenum, we use, as boundary conditions, the inlet mass flow rates data and inlet temperatures data of the 157 orifices of the upper core plate. Afterwards, to validate the model, we compare the stratified liquid temperatures given by the code with the thermocouples temperatures obtained in the hot legs.

The upper core plate comprises 157 orifices and each one has a flow with different thermal-hydraulic conditions (liquid velocity and temperature)

The support columns are solid columns of circular section with a diameter of 8.8 cm. In the upper part the diameter widens in a conical form up to a diameter of 15.24 cm (diameter of the two orifices of the upper plate). In the lower part, these columns are connected to the core upper plate through a square section piece, which is welded to the plate in its four corners. This piece has some orifices in the four sides of the square, through which water enters in the upper plenum.

In the model, the shape of the support column is simplified. The base junction piece is not considered, and it is supposed that the length of the support column is equal to the height of the upper plenum. In figure 1 it is shown the model of the support columns, as well as the conical form of the upper part.

The guide tubes are hollow tubes of square section of 16.03 cm side, with rounded corners. The water enters through the bottom of the column, and exits through the square orifices situated in each side of the column. The guide tubes have eight orifices, two in each face of the guide tube.

The guide tubes contains:

- 24 control rods of 0.889 cm diameter.
- 1 rod for the in-core instrumentation.

The guide tubes have been modelled in this way:

- Total area = 256.96 cm
- 24 control rods: 0.1489 cm²
- Net area: 256.86-0.1489 = 256.81 cm²

Considering the rounded corners, we take an approximated area of 256 cm^2 , so the guide tubes are modelled with a square section of 16 cm side, and length equal to the upper plenum height of 2.12598 m . The orifices are squares of 12.7 cm side (see figure 2).

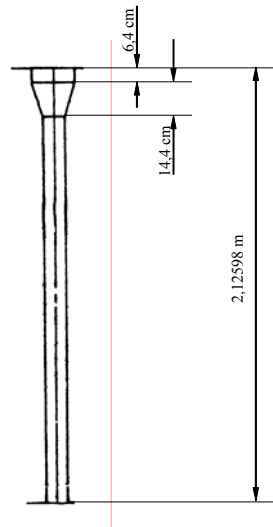


Fig. 1. Model of the support columns.

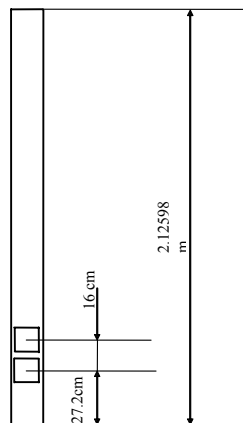


Fig. 2. Model of the guide tubes.

The core upper plate has 157 orifices which are the channels orifices of the fuel bundles. These orifices have a diameter of 15.24 cm . The model of the upper core plate, with the guide tubes and the support columns is illustrated in figure 3.

The upper support plate is equal to the upper core plate.

The height of the upper plenum, i.e., the distance between the upper core plate and the upper support plate, is 2.12598 m .

The hot legs have an internal diameter of 0.7366 cm . Their lengths, from the centre of the upper plenum to the elbow of the steam generator, are 7.294 m . The angle separation between the hot legs is 120° .

The boundary conditions of the model are:

- 157 inlets.
- 3 outlets, at the end of each hot leg.

The upper-plenum mesh plus the three hot leg mesh has a total number of 3 349 977 elements (tetrahedrons) with maximum length of 0.0522717 m, with an angular resolution of 18°.

We use the CFX 5.4.1 code with the k-ε turbulence model.

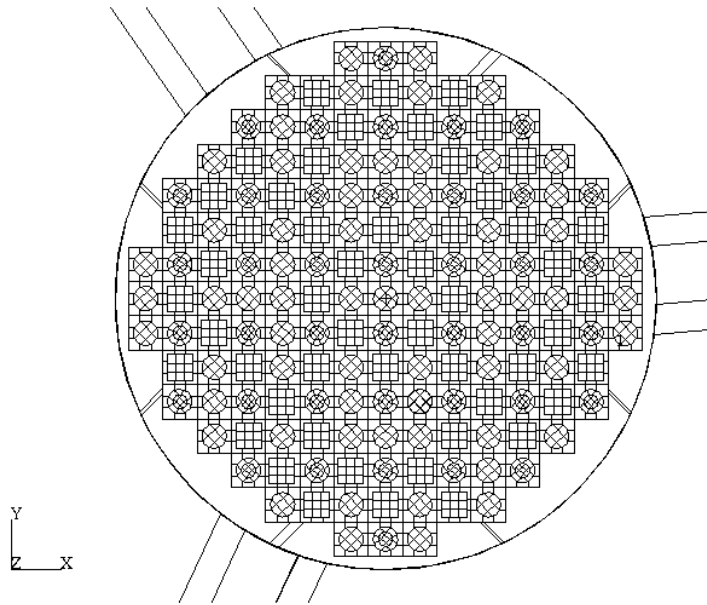


Fig. 3. Model of the upper core plate.

2.1. Results

With this model we have obtained, where the thermocouples are located, the following maximum and minimum values of temperature in the hot legs (See table 1). In this table *position* indicates the geometrical location, according to the hands of the clock, where this temperature takes place.

Table 1. Maximum and minimum temperatures in the hot legs.

LEG	Maximum temperature	Position	Minimum temperature	Position
1	601.687 K	1	599.369 K	7
2	600.924 K	12	598.568 K	6
3	601.214 K	11	599.15 K	5

In figures 4, 5 and 6 we show a comparison between the measured data and the values obtained with CFX.

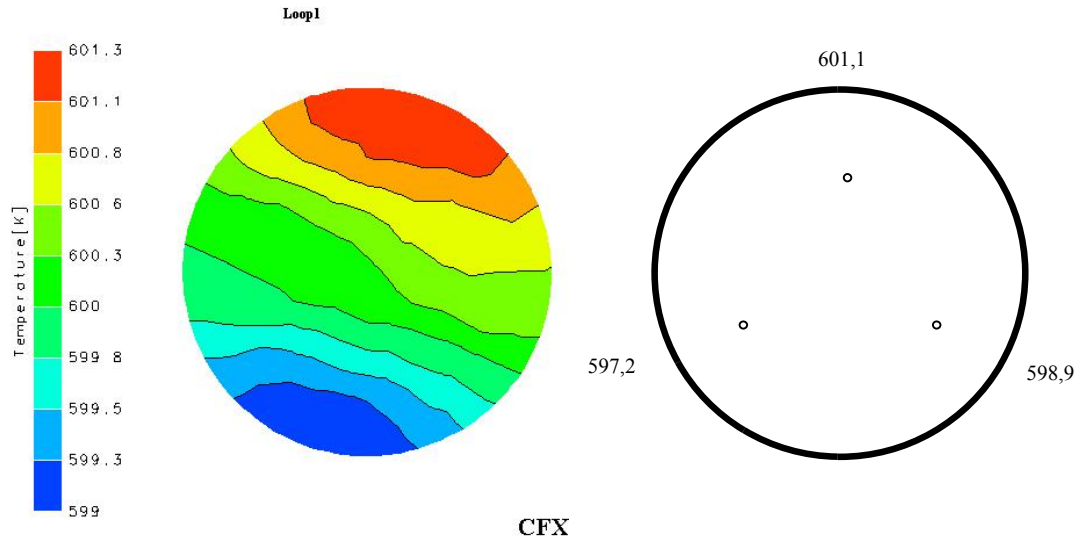


Fig. 4. Thermal stratification calculated with the CFX code (left) and measured with the thermocouples in the hot leg 1 of Vandellos NPP.

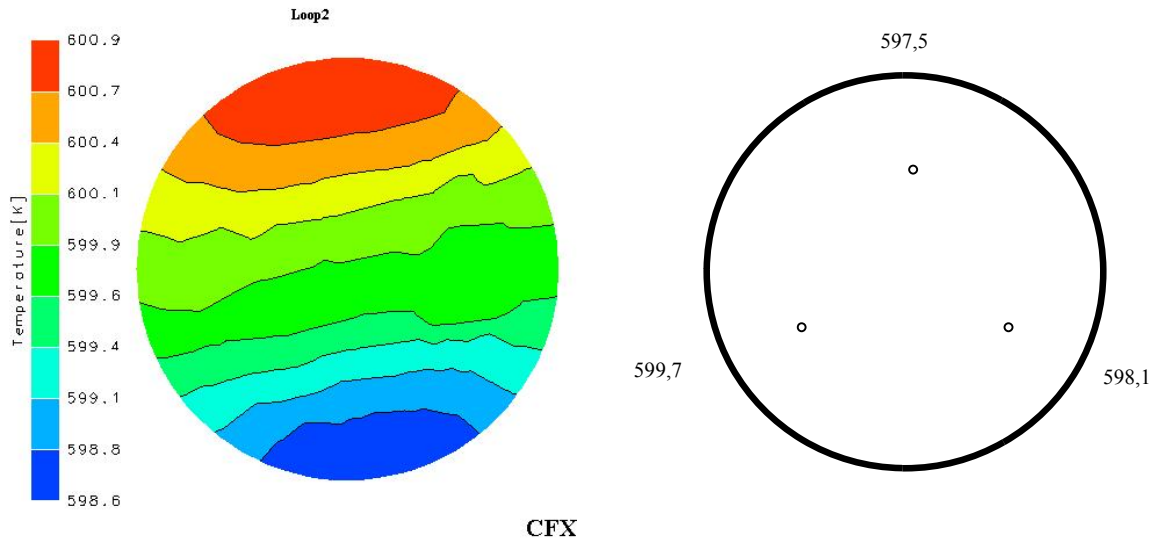


Fig. 5. Thermal stratification calculated with the CFX code (left) and measured with the thermocouples in the hot leg 2 of Vandellos NPP.

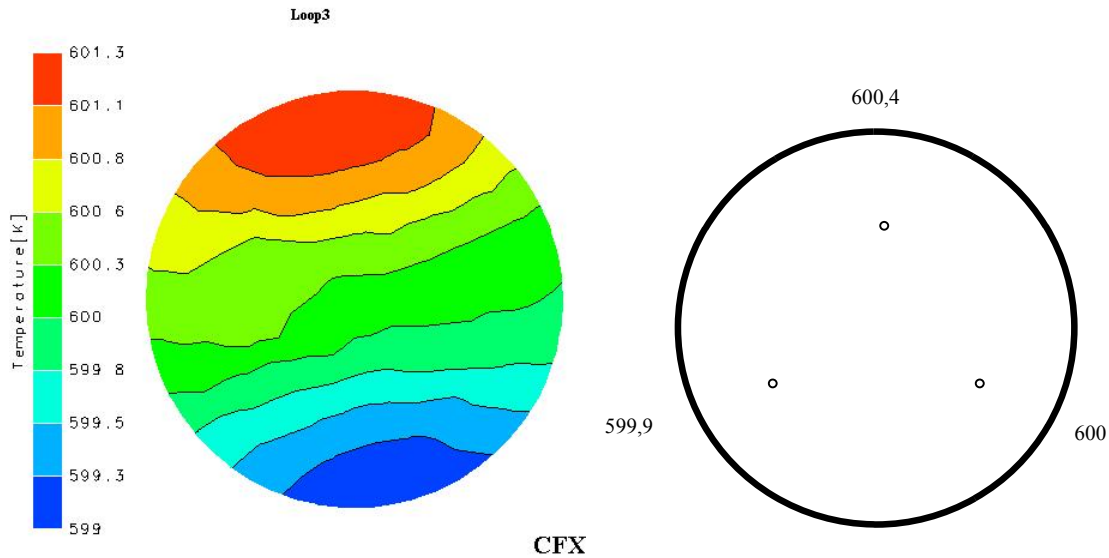


Fig. 6. Thermal stratification calculated with the CFX code (left) and measured with the thermocouples in the hot leg 3 of Vandellos NPP.

Comparing the values of temperature obtained with the code with the data of the thermocouples, we can observe that the range of temperatures is very similar. However, the values differ slightly because the thermocouple was inside a cone with several holes that receives the hot water from different radial regions nearby the thermocouple position. Therefore, the thermocouple measures an average temperature of this radial region.

These differences are due to the finesse of the mesh: the one used is the finest mesh that it is possible to get with the capacity of the used PC. One could make the finest mesh in the areas where the gradients are bigger, so the results would show a bigger convergence.

On the other hand, in the Leg 2 the maximum temperature obtained by means of the thermocouples is given in the lower part of the pipe. The following step would be to study this phenomenon with the model already implemented.

3. CODES DEVELOPED BY THE UPV TO STUDY THE PIPING STRATIFICATION

In the recent years, several cases of thermal stratification have been observed in the pipes systems of some nuclear power plants. The presence of this phenomenon was not expected and therefore, it was not considered in the plant design. However, such phenomena, as the additional deformation and the stress, could play an important role, and to influence in some lines like the hot legs in the PWR.

It has been detected that the stratification exists with several intensity degrees in the pressurizer line, specially during the startup and shutdown processes of the plant. The potential for this stratification is given by the difference of temperatures of the hot loop of the primary cooling pipe (323.15 – 586.15 K) and the electrical preheating of the pressurizer (617.15 K) during the start phase, which can end up causing fissures in the line, due to the fatigue that could appear.

Owing to what we have previously said, it becomes necessary to be able to predict when and to what extent the stratification can take place, i.e., to know which sections of the line will be the most affected

ones, and what will be the maximum temperature difference between the upper and the lower part of the pipe.

We have studied two different situations, in the base of the reported data by Pérez N. et al. [5], and Grebner H. et al. [6]. Next, we describe each of the analyzed cases.

The calculations were performed with the TUBE-3D code [7] [8] that solves the mass, energy and momentum equations, plus the k- ϵ turbulence equations. The code uses a structured mesh in cylindrical geometry, and its results for thermal stratification problems have been compared with experimental results and the results of other codes like CFX.

CASE 1

We supposed a pipe that is initially to 355 K, and it is put under a constant water flow to 501 K. The pipe is horizontal and is 2 m length. Its interior diameter is 0.2842 m. Four cells were modeled in radial direction, twenty cells in azimuthal direction, and ten cells in axial direction, so that a mesh of 4 x 20 x 10 is generated. In figure 1 it is possible to appreciate the mesh type used for this case.

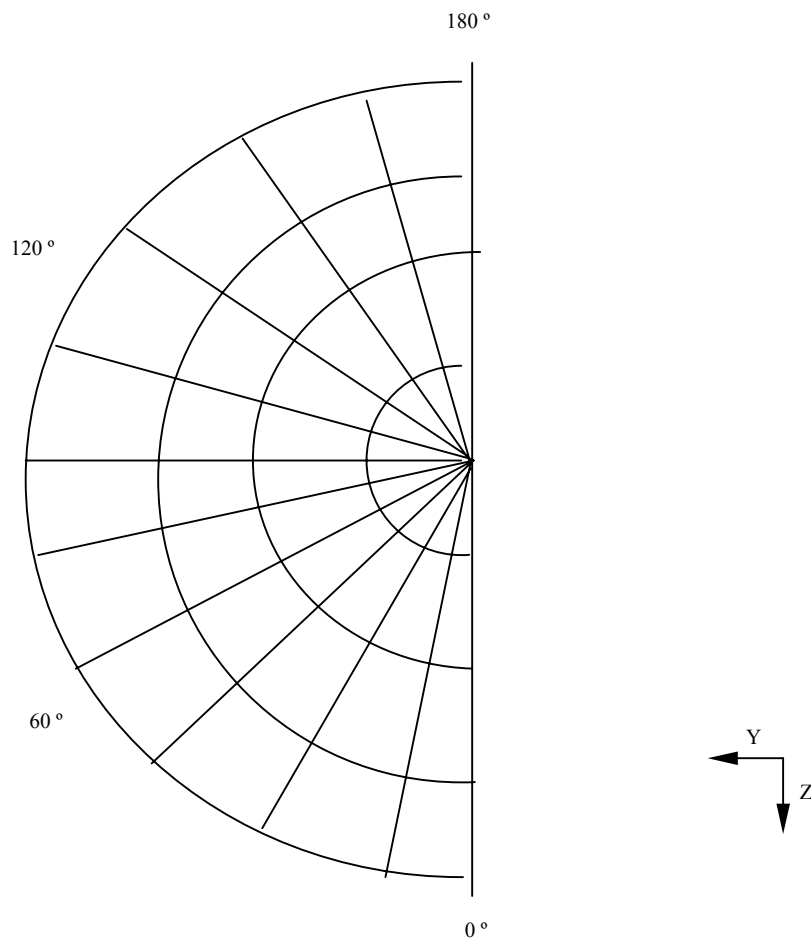


Fig. 7. Model of cross section for the case of stratification.

In this case, we have studied the effect that causes the flow in the entrance section, with the purpose of studying the influence of the velocity in the stratification, for which we considered two different uniform velocities, the first of 0.01 m/s and the second of 0.5 m/s. For both studies, we considered four azimuthal positions. The data comparison reported by Pérez and collaborators with those of the

program TUBE-3D at 0° and 60° are shown in figures 8 and 10, as well as the results evaluated at 120° and 180° are shown in figures 9 and 11.

In figures 8 and 9 we can observe that as the lower sections of the pipe (0° and 60°) remain initially to the entrance temperature of 355 K, the sections in the upper positions (120° and 180°) go increasing faster their temperature. One can observe how the colder fluid remains in the lowest sections, as long as the upper part goes warming gradually, although a time is reached in that the fluid temperatures increase uniformly, not taking place more jumps of temperature.

Figure 10 shows the effect of the temperature in the lower sections of the tube (0° and 60°), as well as figure 11 shows it in the upper sections of the tube (120° and 180°). However, it is not as evident as in the previous case, because the velocity is bigger and, therefore, a certain drag of the cold fluid exists. This also implies a smaller time in which the stability of temperatures is achieved.

One can also observe that the lower is the velocity the bigger is the difference of temperatures, allowing a bigger stratification of the thermal layers, since the high flows allow a bigger mixture of the thermal layers, causing a smaller stratification.

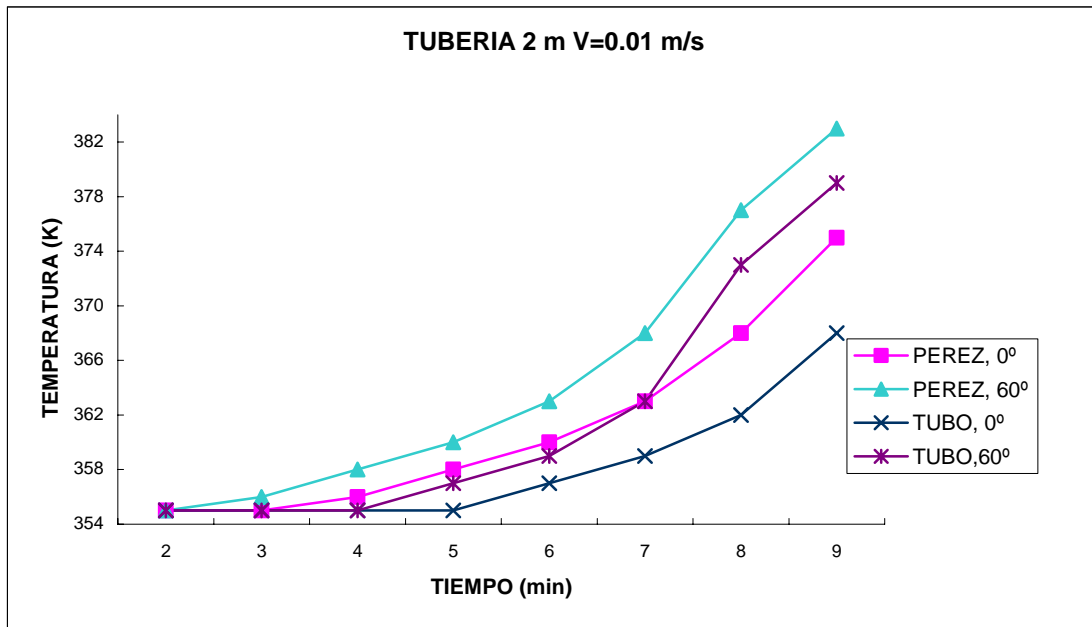


Fig. 8. Comparison of the results of the temperature with data of Pérez N. et al and the program TUBE-3D at 0° and 60° , with a velocity of 0.01 m/s.

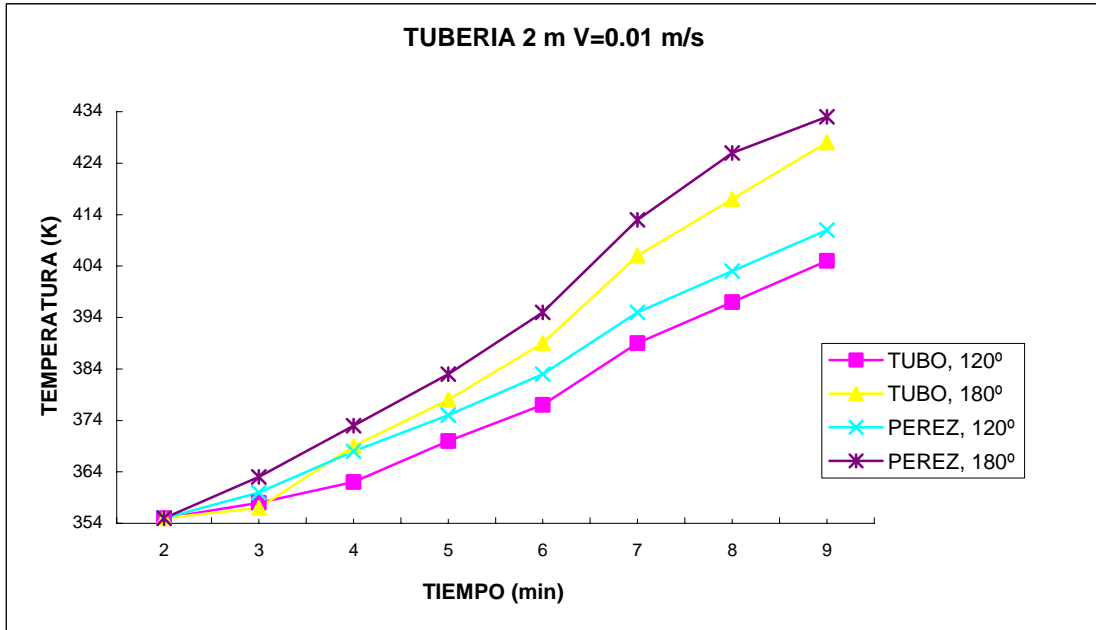


Fig. 9. Comparison of the results of the temperature with data of Pérez N. et al and the program TUBE-3D at 120° and 180°, with a velocity of 0.01 m/s

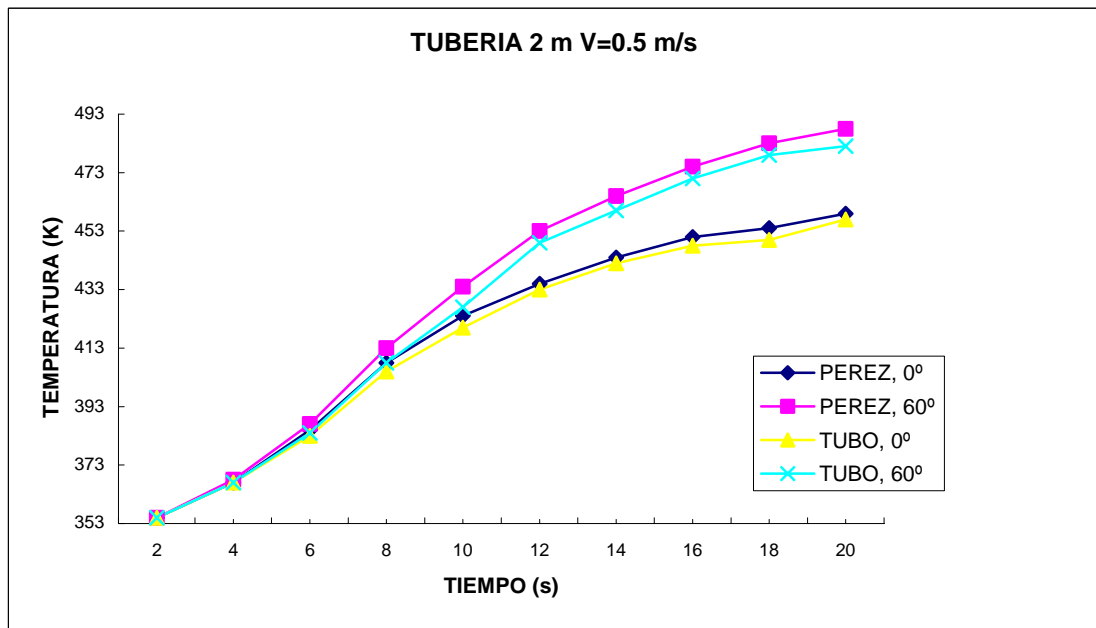


Fig. 10. Comparison of the results of the temperature with data of Pérez N. et al and the program TUBE-3D at 0° and 60°, with a velocity of 0.5 m/s

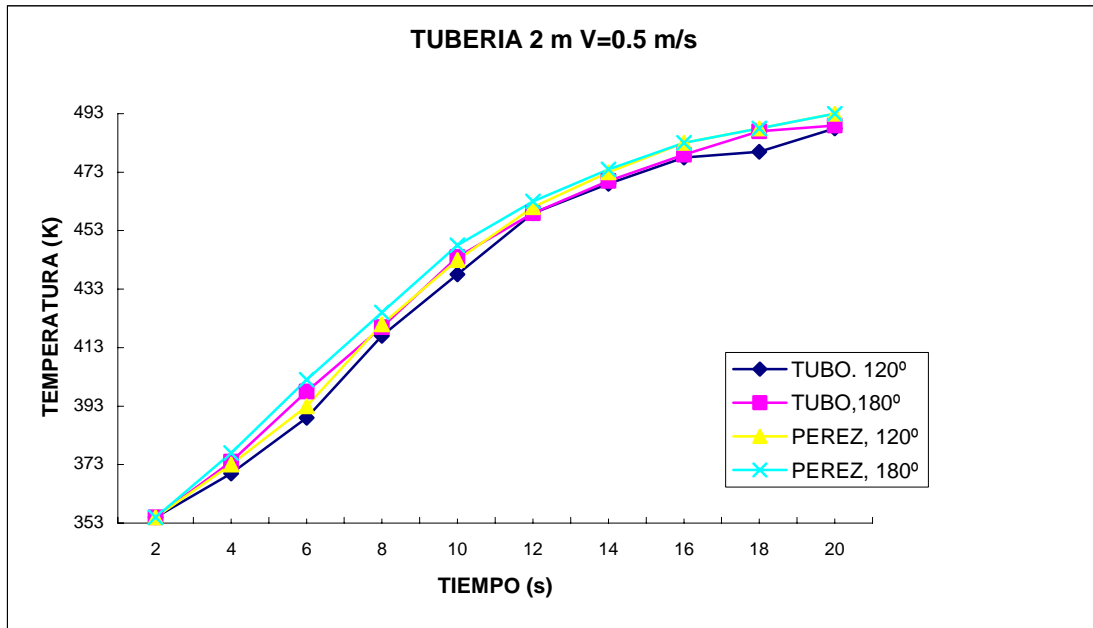


Fig. 11. Comparison of the results of the temperature with data of Pérez N. et al and the program TUBE-3D at 120° and 180°, with a velocity of 0.5 m/s

CASE 2.

The second case analyzed for the stratification was based on the experiment carried out by Grebner [6], on the start-up line of a PWR. In this case, it is considered a pipe with a length of 12 m and a diameter of 0.388 m, its inlet temperature is 418 K and the outlet temperature is 603 K. We considered a mesh with five radial cells, twenty-four azimuthal cells and ten axial cells. Figure 12 samples the results obtained by Grebner and figure 13 the results obtained with the program TUBE-3D.

In figure 14 are shown the average temperatures obtained with TUBE-3D. Although they do not correspond exactly to the same values of those which appear in figure 13, they show the different layers of temperature, which is the result of the stratification that has originated in the pipe due to the difference of temperature present in the entrance and exit of the line.

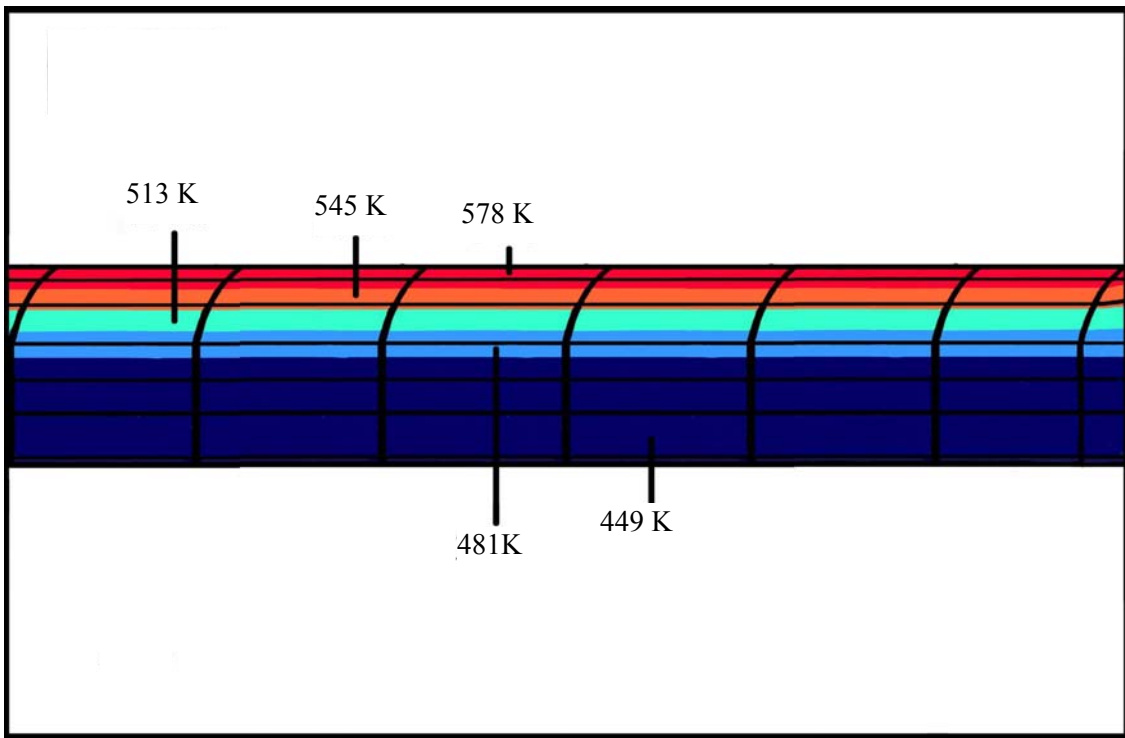


Fig. 12. Distribution of the temperature due to the stratification with data of Grebner et al, 1995.

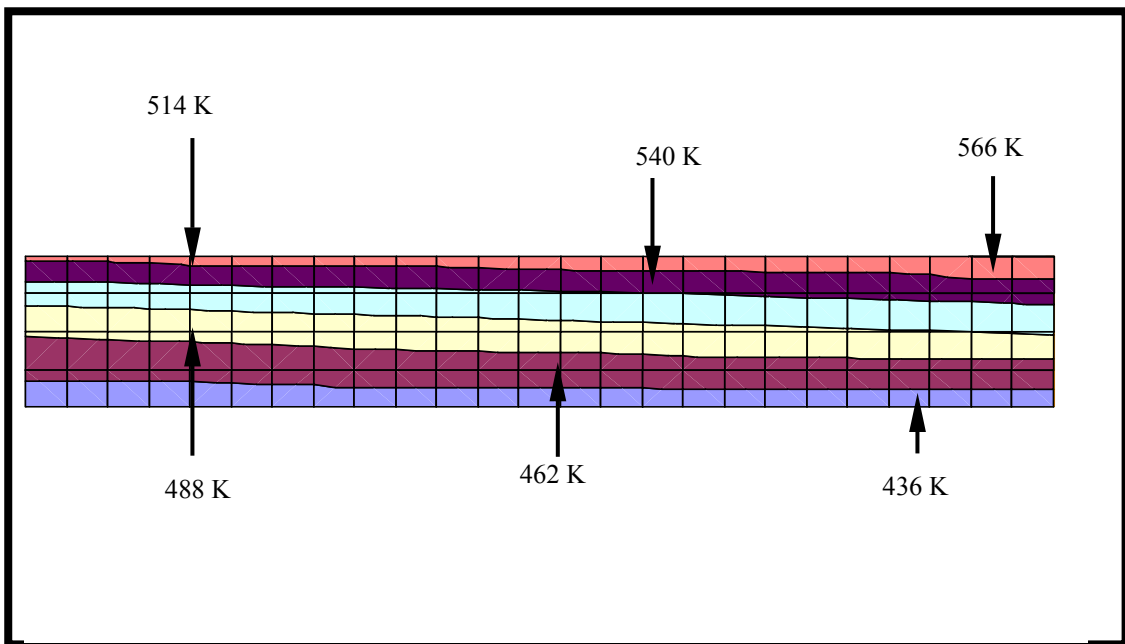


Fig. 13. Distribution of the temperature due to the stratification obtained with the program TUBE, with $r = 5$.

In the liquid thermal stratification the equation of the moment takes part strongly because of the less density of the hottest part of the liquid, and besides, it will suffer a buoyancy force due to the difference of density with the coldest part.

By means of the model developed in this work, it has been possible to carry out studies of thermal stratification in pipes. The code of CFD TUBE-3D presents a high grade of accuracy, when considering the stratification in sections of straight pipe.

This is a contribution of great importance by virtue of the studies of security in the pipes of nuclear power plants which are carrying out, because a one-dimensional code -just as TRAC-BF1-, does not allow the accomplishment of these studies. Although at the moment other codes may exist in the market -as CFX and FLUENT- that simulate a pipe in 3D, the advantage that presents the program TUBE-3D is that it starts from the equations used in the TRAC-BF1 code, which would make easier their incorporation to the code TRAC-BF1, although this would not be necessarily trivial.

4. CONCLUSIONS AND CONCLUDING REMARKS

In first part of this paper, we have compared the values of temperature obtained with the code CFX 5.4.1 with the measured data in the hot legs of Vandellos II. We obtain that the range of temperatures is very similar. However, the values differ slightly because the thermocouple was inside a cone with several holes and it measures an average temperature of this radial region.

In the second part of this paper, we present the TUBE-3D code, developed at UPV. The results obtained with this code shows a high grade of accuracy in the simulation of the stratification in sections of straight pipe. The advantage that presents the program TUBE-3D is that it starts from the equations used in the TRAC-BF1 code, which would make easier their incorporation to the code TRAC-BF1, although this would not be necessarily trivial.

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REFERENCES

- [1] Lyman, W.G., Testa, D.A., WOG Minigroup Program Report on Hot Leg Temperature Streaming for Westinghouse 3-Loop Plants, WCAP-14858 (1997).
- [2] André, S.V., et al., RCS Flow Verification Using Elbow Taps at Westinghouse 3-Loops PWRs, WCAP-14750 (1996).
- [3] Lyman, W.G., Testa, D.A., Evaluation of Measurements and Test Data at Vandellos Unit 2 for the WOG Minigroup Program on Hot Leg Temperature Streaming at Westinghouse 3-Loop Plants, WCAP-14589 (1997).
- [4] Barrachina, T., et al. "Estudio de la estratificación de temperature en las ramas calientes en un reactor PWR de tres lazos mediante el código CFX 5.4.1", 27 Reunión Anual de la Sociedad Nuclear Española. Valencia (2001)
- [5] Grebner, H., Höfler, A., Investigation of Stratification Effects on the Surge Line of a Pressurised Water Reactor, *Computers and Structures* **56** (1995) 425-437.
- [6] Pérez, N.J.J., Orden, M.A., "Análisis del Fenómeno de la Estratificación Térmica en Tuberías por Métodos Numéricos", XIX Reunión Anual SNE, Cáceres (1993).
- [7] López, L., Desarrollo de un Código Tridimensional de Malla Estructurada con Esquemas de Alto Orden para Estudios de Estratificación y Turbulencia en Centrales Nucleares, PhD. Thesis, Universidad Politécnica de Valencia (2002).
- [8] García, V.M., et al., Use of high accuracy schemes to handle free surfaces in computing unsteady two-phase flows, *Computer methods in applied mechanics and engineering*. **162** (1998) 271-286.