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METHODOLOGY FOR STUDIES OF NATURAL CIRCULATION IN CLOSED CIRCUITS

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ABSTRACT

This work presents an analysis of stability of the phenomenon of natural circulation for one-dimension single-phase flow in a closed loop. The computer program uses a stabilized finite element formulation for the solution of the Navier-Stokes and energy equations in cartesian coordinates. The formulation has been developed and tested in a computer code developed at the Nuclear Engineering Institute (IEN-CNEN) and is now available either for future analysis or design of nuclear systems.

1. INTRODUCTION

In the area of nuclear engineering, some problems of fluid mechanics and heat transfer are frequently present, so we always have to get better analytical and experimental methods for solving these specific problems.

Problems involving thermal hydraulics in nuclear reactors depend on computer programs to be calculated more accurate and quickly. Therefore, we need computers with response time as fast as possible. As computers are being improved, this time tends to decrease.

The development of a program that uses FORTRAN90 language will be presented in this paper as well as the calculations required to analyze a closed loop where the natural circulation phenomenon occurs.

It is used the finite element method to solve the Navier-Stokes equations in Cartesian coordinates and one equation of energy for the calculations of the mass flow and temperature fields [1].

2. NATURAL CIRCULATION

The phenomenon of natural convection occurs due to differences in density between hot sources of a reactor and the helical coil heat exchanger. The mesh generated to perform the simulation of this natural phenomenon was done using a program of pre-and post-processing called GID (Graphical Interface Design). It is generated a mesh of finite elements of linear type, and it is created an interface compatible with the input data file of our computer code. The figure below shows the scheme that served as a model for the development of this analysis.

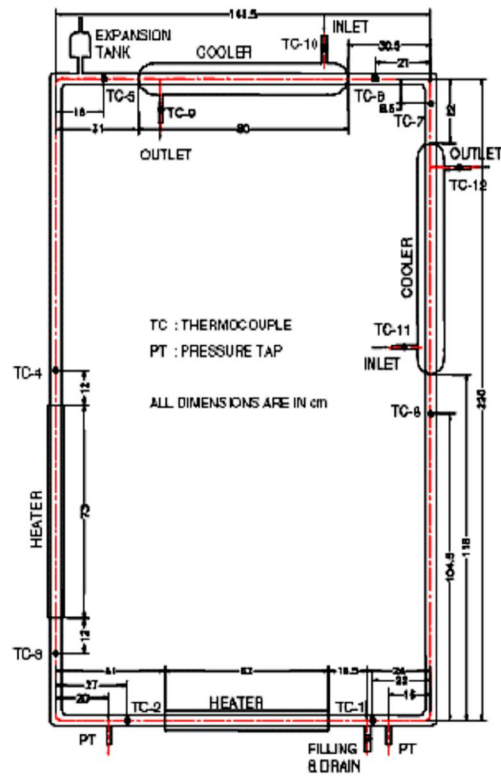


Figure 1 - Natural circulation loop scheme

2.1 Advantages of Natural Circulation

One advantage of this circulation is that it is a natural phenomenon. So, it is independent of active pumps and this can reduce the cost of projects of a nuclear plant. Besides that, it can improve the distribution of flow in the core [2].

2.2 Disadvantages of Natural Circulation

As this phenomenon is natural, it has a low speed for conducting the fluid, as a result, there is a lower maximum power per channel and that can cause instability in the reactor core [3].

3. PHYSICAL MODEL

3.1 Governing equations

We present here the continuum model used in our description of incompressible viscous flows. The problem is defined on the open bounded domain Ω , with boundary Γ , contained in the one-dimensional Euclidean space.

It is used the Navier-Stokes equations for incompressible fluids and the equation of convection-diffusion energy in Cartesian coordinates.

$$A \frac{\partial \rho}{\partial t} + \frac{\partial(\dot{m})}{\partial s} = 0 \quad (1)$$

$$\frac{\partial \dot{m}}{\partial t} + u \frac{\partial \dot{m}}{\partial s} + \frac{\partial u}{\partial s} \dot{m} + A \frac{\partial P}{\partial s} + \rho g A \cos \theta + P_h \Gamma_w = 0 \quad (2)$$

$$A \rho c_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial s} \right) = u A \frac{\partial p}{\partial s} + P_a q_w'' + u P_h \Gamma_w + Q \quad (3)$$

For incompressible flow we can discard the temporal variation of density, since it is too small for this type of flow, also, the terms with pressure derivatives are neglected, as it is a closed circuit. The terms of variation in temperature due to friction will be neglected since they are very small in relation to other terms in the equation. Considering an adiabatic system, the term of heat source is zero. We can then rewrite the equations (1), (2), and (3) as follows:

$$\frac{\partial(\dot{m})}{\partial s} = 0 \quad (4)$$

$$\frac{\partial \dot{m}}{\partial t} + \rho g A \cos \theta + P_h \Gamma_w = 0 \quad (5)$$

$$A \rho c_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial s} \right) = P_a q_w'' \quad (6)$$

A representation of the governing equations in dimensionless form is useful for the analysis of flow development in order to have a model similar to natural phenomena. Variables are put in a dimensionless form using reference scales properly chosen according to the data of the problem.

The fields of velocity, mass flow and temperature are represented by the following dimensionless variables $u = u' u_0$, $\dot{m} = \rho_0 u_0 L^2 \dot{m}'$, and $T = [T'(T_{máx} - T_{mín}) + T_0]$, respectively.

Note that u_0 is the reference velocity and $T_{máx}$ e $T_{mín}$ are the maximum and minimum temperatures in the problem. The dimensionless spatial coordinates are obtained considering the reference length L , so $s = L s'$. The representation of the dimensionless time is given by $t = t' L / u_0$. The scale of reference for the perimeter and the hydraulic friction tensor are respectively: $P_h = P_h' L$ e $\Gamma_w = \Gamma_0 \Gamma_w'$ where $\Gamma_0 = \rho_0 u_0^2$. The non-dimensional gravitational field is obtained taking into account the gravity module, i.e. $g = g' \|g\|$. The non-dimensional area is given as, $A = A' L^2$ and the dimensionless density is $\rho = \rho' \rho_0$.

Therefore, we can write the equations (4), (5) and (6) in dimensionless form, as:

$$\frac{\partial \dot{m}'}{\partial s'} = 0 \quad (7)$$

$$\frac{\partial \dot{m}'}{\partial t'} + R_i A' T' \beta' g' \cos \theta + P_h' \Gamma_w' = 0 \quad (8)$$

$$\rho' c_p' \left(\frac{\partial T'}{\partial t'} + u' \frac{\partial T'}{\partial s'} \right) = \frac{1}{Pe} \frac{P_a' q_w''}{A_t'} \quad (9)$$

3.2 Stabilized finite element formulation

The time discretization for the non-dimensional equations was obtained using the finite differences method [4].

$$\frac{\partial \dot{m}^{n+1}}{\partial s} = 0 \quad (10)$$

$$\frac{\dot{m}^{n+1} - \dot{m}^n}{\Delta t} + R_i A T^n \beta g \cos \theta + P_h \Gamma_w^n = 0 \quad (11)$$

$$\rho c_p \left(\frac{T^{n+1} - T^n}{\Delta t} + u^n \frac{\partial T^{n+\theta}}{\partial s} \right) = \frac{1}{Pe} \frac{P_a q_w''^n}{A_t} \quad (12)$$

Rewriting these equations in terms of the time steps and using finite element of equal order to all variables in space discretization and applying the minimization of quadratic residues of the momentum and energy with respect to the free nodal values, we have the following equations:

$$\int_{\Omega} \frac{(N_i)}{\Delta t} \left(\Delta \hat{m} \right) d\Omega = - \int_{\Omega} N_i \left(R_i A T^n \beta g \cos\theta + P_h \Gamma_w^n \right) d\Omega \quad (13)$$

$$\int_{\Omega} \left(N_i + \theta u^n \Delta t \frac{\partial N_i}{\partial s} \right) \rho c_p \left(\Delta \hat{T} + \theta u^n \Delta t \frac{\partial \Delta \hat{T}}{\partial s} \right) d\Omega = \int_{\Omega} \left(N_i + \theta u^n \Delta t \frac{\partial N_i}{\partial s} \right) \hat{Q} d\Omega \quad (14)$$

These equations are written in terms of matrices and vectors for the computational implementation of finite elements.

4. RESULTS

When working with computer programs, an important step to do is to validate the code developed. So, for the validation of our computational code, the study the natural circulation phenomenon in a thermal hydraulic loop was performed. It was tested the computational model by comparing the values of the mass flow along the time with results obtained with other numerical modeling.

4.1 Case example

We compared results obtained in a theoretical model used by Maiani [5], and a numerical model developed by Ambrosini and Ferreri [6]. Thus, given a certain disturbance in the stationary state of a heated fluid flowing in a cylindrical tube of a closed loop, after some time the stabilization is achieved, as we can see in Figure 3.

The natural circulation is established for different sections of circular tubes, since they have a uniform diameter. Each section is axially discretized with a uniform distribution. The energy balance equation is solved using the one-dimensional Petrov-Galerkin method with optimal upwind. The momentum equation is discretized in time by a semi-implicit technique. The heat transfer coefficient of the fluid is calculated using a constitutive equation. It is used the Darcy friction factor to solve this problem [5].

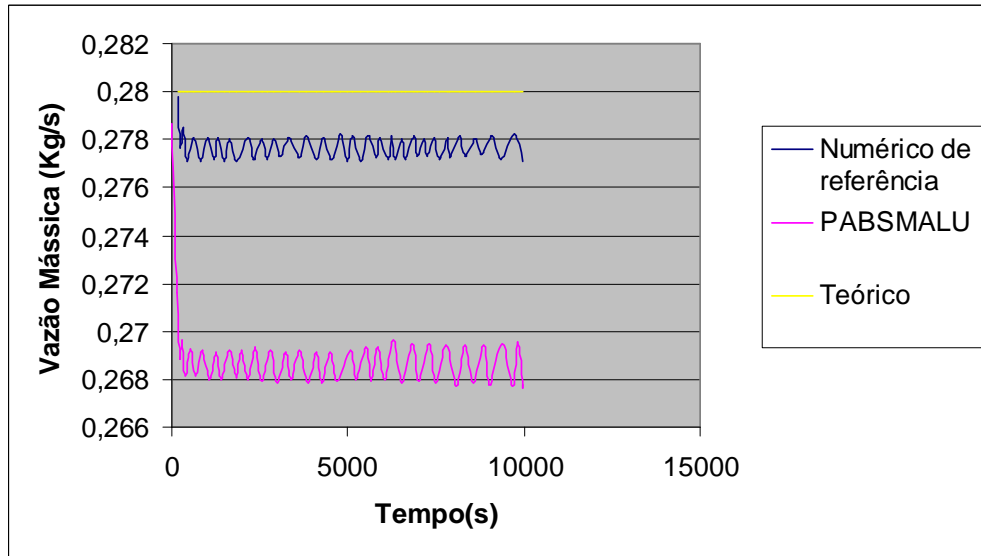


Figure 3 - Flow mass versus time

5. CONCLUSIONS

In the studies of Maiani [5] and his collaborators, it was done the simulation of a primary reactor system in a rectangular geometry, where the locations of the heater and the refrigerator were pre-set. Using the same geometry and thermal dynamics data used by Maiani, we obtained some results showed graphically in this work. It is observed the same behavior in both simulations, and thus we can compare if the methodology used in this work is or is not appropriate for simulation of natural convection in closed circuits.

It is expected that the program developed in this work, and incorporated to the resources of the Laboratory of Computation of the IEN, will be used in further studies of analysis and projects of nuclear reactors. Two-dimensional and biphasic models are being developed to be implemented using the computational basis of this work [1].

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