17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0658
DYNAMIC CHARACTERISTICS OF A NATURAL CIRCULATION LOOP WITH COOLER INTEGRATED TO A POOL WITH EVAPORATION

Leon Lima
Eletrobras Eletronuclear; Rua da Candelaria 65, 20091-020 RJ, Brazil.
lmatos@eletronuclear.gov.br

Norberto Mangiavacchi
Fac. Engenharia Mecânica, Universidade do Estado do Rio de Janeiro - UERJ; Rua São Francisco Xavier 524, 20550-900 RJ, Brazil.
norberto@uerj.br

Abstract. *Natural circulation loops (NCLs) are passive cooling systems consisting of a hydraulic circuit with heaters and coolers. In most of the industrial applications, the heater and/or the cooler is integrated to a pool which is absorbing or rejecting heat. This paper analyzes how the dynamic behavior of a NCL is affected by the integration of a pool to the cooler. The study considers a system where a constant heat is transferred to the loop through the heater and rejected through the cooler to a pool with evaporation. A 1-D model was developed to calculate the steady state regime and to simulate the transients of the system. This paper shows interesting results from the comparison of the NCL with and without integration to the pool.*

Keywords: *Nuclear Energy, Passive Cooling, Natural Convection, Stability Analysis*

1. INTRODUCTION

Natural circulation loops (NCLs) are engineering solutions for passive heat transfer. It consists of a hydraulic circuit with heaters and coolers forming a thermosyphon. Common applications on the energy industry are geothermal, solar and nuclear power plants. In the case of nuclear energy, NCLs are gaining importance pushed by the demand for clean energy and the events in Fukushima, Japan, in 2011.

Because NCLs do not depend on external energy sources to operate, they are reliable cooling systems, and therefore an excellent solution for emergency removal of decay heat from nuclear reactors. For the design of an optimum NCL it is necessary to know the regions of stable operation, i.e., geometric and operating parameters should be chosen so that the system is able to transfer the maximum amount of heat at stable operating regimes. For instance, larger diameters allow for larger mass flow rates, which enhances heat removal capacity, but it might lead the system to thermo-hydraulic instabilities. Until the work of Keller (1966), instabilities was not regarded as a possibility in single-phase NCLs; only two-phase systems were thought of as being susceptible to (many types of) instabilities. Almost a decade after Keller (1966), the work of Creveling *et al.* (1975) showed experimental evidences that single-phase thermosyphons could undergo unstable regimes.

The relevance of this topic has taken many researchers to perform a wide range investigations on NCLs, both single-phase and two-phase systems Basu *et al.* (2014). Several aspects related to NCLs, many of them regarding thermo-hydraulic stability, have been studied by those authors. However, the integration of NCL to a pool had not been addressed until the work of Lima *et al.* (2017), which developed a simplified numerical model to account for a pool integrated to the heater. The motivation was the project of a storage facility for spent fuel elements in the nuclear station of Angra dos Reis, Brazil.

The present work considers the integration of a pool to the cooler. Many emergency cooling systems of new nuclear power plant designs consist of a NCL rejecting the decay heat absorbed from the reactor core to a large cooling pool. The heat transferred to the water in the pool is then rejected to the ambient air by evaporation, forming a fully passive cooling system.

The objective of the present work is to provide information about how the dynamics of a single-phase NCL is affected by the integration of a pool to the cooler, in comparison to the system without pool. To produce such information, transient data were generated using the model described in section 2, simulating the dynamic behavior of the system after a perturbation on the steady state.

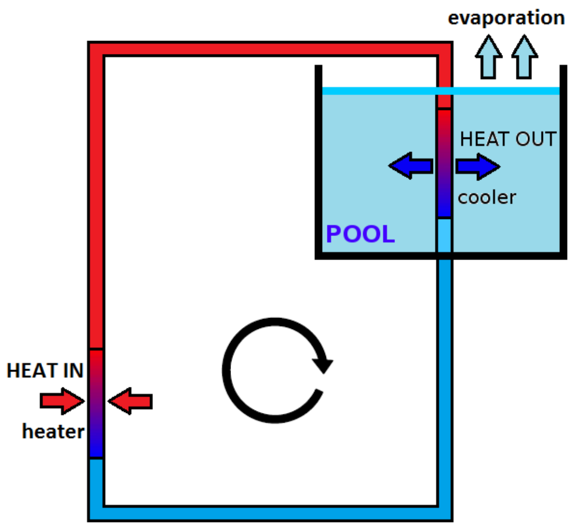

Figure 1. Schematic drawing a natural convection loop with pool integrated to the cooler.

2. GEOMETRY AND MATHEMATICAL MODEL

The Natural Circulation Loop consists of a hydraulic circuit with a heater at the bottom and a cooler at the top of the circuit. In the particular case of the present study, the cooler rejects heat to a cooling pool which in turn rejects heat to the ambient through evaporation. This configuration resembles a typical emergency cooling system of a Generation III+ nuclear power plant, designed to transfer heat in the event of a Loss of Coolant Accident (LOCA). In such a scenario, a break in the reactor refrigerating system occurs, and the refrigerating fluid starts to leak, therefore compromising the reactor cooling. Although this is a very rare event – along the course of more than a hundred million hours of nuclear power generation there are only three occurrences of LOCA, viz. Three Mile Island (USA, 1979), Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011) – nuclear power plants are equipped with safety systems to mitigate the consequences of such an event. In the case of recent designs – Generation III+ – many power plants have a passive emergency reactor cooling system. The system studied in this work, schematically shown in fig. 1, reproduces such an emergency system. The thermal load absorbed by the heater represents the reactor decay heat (after a LOCA, the reactor is immediately shutdown, but it continues to dissipate heat as result of the activity of the different unstable isotopes contained in the reactor core). The cooler is the set of heat exchangers responsible for dissipating the decay heat to a cold source. Many designs count with a large cooling pool to absorb this heat and then dissipate it to a second stage cold source. This is the configuration under analysis in the present work. In particular, the configuration considered here is equivalent to the passive safety system designed for the AP1000 nuclear power plant, created by Westinghouse. In the AP1000, the heat is rejected through evaporation in the pool to the containment building, which is in turn cooled by an external air flux driven by natural convection.

The objective of the present work is to analyze this system from the point of view of thermal-hydraulic stability using numerical simulation. The method of analysis is to introduce a perturbation on the steady state regime and observe the dynamic response of the system.

The mathematical model takes the following assumptions into account: (i) all physical properties are assumed to be constant in the cross section area; (ii) the circuit walls are adiabatic along the entire loop except for heater and cooler; (iii) axial heat conduction is neglected, as well as viscous heating; (iv) no boundary layer development length is considered in heated and cooled sections. Introducing the space coordinate s in the axial direction and the mass flow rate w, which can be calculated by $w = \rho \int_A u dA$, where u is the axial velocity component and A is the area of the cross section, the continuity equation for incompressible flow reduces to

$$\frac{\partial w}{\partial s} = 0 \tag{1}$$

Employing Boussinesq hypothesis, density in the gravity term can be written as $\rho = \rho_0[1 - \beta(T - T_0)]$, where the subscript 0 represents a value based on the mean temperature and β is the thermal expansion coefficient (evaluated at T_0). Let L and D respectively be the length and diameter of the loop. Integration along the whole loop volume produces

$$\frac{L}{A}\frac{dw}{dt} = -\left(f\frac{L}{D} + K\right)\frac{w^2}{2\rho_0 A^2} + \rho_0 g\beta \oint T dz \tag{2}$$

where t is time and g is the modulus of gravity field. The friction factor f and the local losses coefficient K were introduced. The buoyancy term is a function of the temperature field T.

Regarding the temperature field T, after applying the simplifying assumptions, energy conservation is expressed by

$$\text{heater:} \quad \frac{\partial T}{\partial t} + \frac{w}{\rho_0 A}\frac{\partial T}{\partial s} = \frac{Q}{A L_h \rho_0 c_p} \tag{3a}$$

$$\text{cooler:} \quad \frac{\partial T}{\partial t} + \frac{w}{\rho_0 A}\frac{\partial T}{\partial s} = -\frac{4U_c(T - T_{\text{pool}})}{D\rho_0 c_p} \tag{3b}$$

$$\text{pipes:} \quad \frac{\partial T}{\partial t} + \frac{w}{\rho_0 A}\frac{\partial T}{\partial s} = 0 \tag{3c}$$

where Q is the heat input, U_c is the heat transfer coefficient of the cooler, c_p is the specific heat at constant pressure and T_{pool} is the temperature in the pool.

To complete the system, the energy balance in the pool is expressed as

$$M_c c_p \frac{dT_{\text{pool}}}{dt} = U_c \pi D \left(\int_c T ds - T_{\text{pool}} L_c \right) - \dot{m}_{\text{evap}} h_{\text{pool}} \tag{4}$$

where M_c is the water mass, $\dot{m}_{\text{evap}}$ is the evaporation rate (kg/s) and h_{pool} is the specific enthalpy of the pool.

2.1 Evaporation

For the calculation of the evaporation rate $\dot{m}_{\text{evap}}$, the correlation proposed by Shah (2014) is employed, which represents the mass transfer rate through undisturbed surfaces of unoccupied pools. It is expressed by

$$\dot{m}_{\text{evap}} = C A_{\text{pool}} \rho_w (\rho_r - \rho_w)^{1/3} (W_w - W_r) \tag{5}$$

with $C = 35$ and A_{pool} standing for the pool water surface. The other variables are the psychrometric parameters evaluated at the water surface (subscript w) and at an ambient reference location (subscript r), with ρ standing for density and W standing for absolute humidity. This equation models the mass transfer through evaporation driven by ambient natural convection, which is the representative condition in a typical containment building. Another possible evaporation mechanism is that driven by forced convection, like outdoor pools.

Since the subscript w stands for conditions at the water surface, i.e., under saturated conditions, it can be seen that if relative humidity in the ambient is 100%, evaporation ceases, and the heat transfer from the pool to the ambient is interrupted. Therefore, it is important to integrate the design of HVAC systems when designing natural convection cooling systems.

3. RESULTS

To analyze the effect of the pool on the system dynamics, the transient regimes of the experimental NCL described in Pilkhwal *et al.* (2007) were simulated. The loop permits four configurations with respect to the orientation of heater and cooler, viz. HHHC (horiz. heater/horiz. cooler), HHVC (horiz. heater/vert. cooler), VHHC (vert. heater/horiz. cooler) and VHVC (vert. heater/vert. cooler). The selected operating parameters are $Q = 600$ W and $T_{\text{air}} = 30°$C. The heat transfer coefficient of the cooler is $U_c = 450$ W/m^2/K. This value was set for the cooler in the configuration with integration to the pool. Then, from the steady state regime, a global heat transfer coefficient was calculated and attributed to the cooler in the configuration without pool, so that comparisons could be valid. In all cases, the perturbation consisted on 10% reduction of the steady state mass flow rate.

Two cases were simulated for each loop configuration: without pool and with pool integrated to the cooler. The water mass inside the pool is $M_c = 1000$ kg. The surface area of the pool is $A_{\text{pool}} = 4$ m^2. The number of mesh nodes and the CFL number are, respectively, 1000 and 0.50. Table 1 summarizes the geometric and numerical parameters employed in the study.

Table 1. Geometric and numerical parameters of the analyses.

diameter (D)	26.9000 mm
width (W)	1.4150 m
height (H)	2.2000 m
heater length (L_h)	0.6200 m
cooler length (L_c)	0.8000 m
total local loss coef. (K)	4.2000
mesh nodes	1000
CFL	0.50

The friction factor correlation employed was that proposed by the work of Ruiz *et al.* (2015), in which the authors employed a combination of Poiseuille and Blasius' expressions, using a Fermi-Dirac distribution to build a derivative continuous transition between the two correlations. The transition parameter, γ, was determined from the fitting of an experimental campaign in a straight infinite tube. The expression for the correlation is

$$\begin{aligned} f &= \frac{a}{\mathrm{Re}^b} \\ a &= 64^\gamma 0.316^{1-\gamma} \\ b &= \gamma + \frac{1}{4}(1+\gamma) \\ \gamma &= \frac{1}{1+\exp\left(\frac{\mathrm{Re}-2530}{120}\right)} \end{aligned} \tag{6}$$

Tables 2 and 3 list the results for the main parameters of the problem and fig. 2 presents the obtained transients.

Table 2. Results obtained for the four loop configurations without pool integrated ($M_c = 0$ kg).

	HHHC	HHVC	VHHC	VHVC
U_{global} [kW/m^2/K]	0.1889	0.1899	0.1890	0.1900
U_c [kW/m^2/K]	0.1889	0.1899	0.1890	0.1900
St	0.6240	0.7018	0.7202	0.8704
$\mathrm{Gr}(\times 10^{-11})$	12.81	9.56	8.29	5.02
Re	5702.58	5152.88	4891.03	4113.35
decay/growth rate ($\times 10^3$) [s^{-1}]	5.9625	-3.0453	-6.0496	-0.9040

Table 3. Results obtained for the four loop configurations considering integration of a 1000 kg pool to the cooler ($M_c =$ 1000 kg).

	HHHC	HHVC	VHHC	VHVC
U_{global} [kW/m^2/K]	0.1889	0.1899	0.1890	0.1900
U_c [kW/m^2/K]	0.4500	0.4500	0.4500	0.4500
St	1.4866	1.6607	1.7154	2.0532
$\mathrm{Gr}(\times 10^{-11})$	12.75	9.53	8.29	5.02
Re	5695.61	5154.18	4888.07	4130.12
decay/growth rate ($\times 10^3$) [s^{-1}]	5.0987	-3.9176	-4.5095	-2.4120

A decay/growth rate was calculated based on the linear oscillating regime of each case. It can be seen from the curves of fig. 2 and the values in tables 2 and 3 that, when integration to the pool is considered, the damping of the oscillations is stronger than without pool. In other words, results lead to the conclusion that the pool tends to stabilize the system.

4. CONCLUSIONS

From the generated results, it can be concluded that the integration of a pool to the cooler of the NCL has a stabilizing effect on the dynamic characteristics of the system, in a similar way to the integration of a pool to the heater, as studied by Lima *et al.* (2017), although, in the present configuration, heat sink is a function of the water temperature in the pool, whereas in the configuration of Lima *et al.* (2017) a constant heat Q is injected in the pool. The thermal inertia that the pool provides seems to actuate as a buffer for the system oscillations, increasing the robustness against perturbations. The practical conclusion from these results is that for an optimum design of a NCL for passive cooling, the stability analysis must take the pool into account, for it enlarges the stability region of the system.

It should be said however that these conclusions rely solely on numerical results, with the influence of a set of simplifying assumptions. The results herein presented shall be confronted with experimental data.

5. REFERENCES

Basu, D.N., Bhattacharyya, S. and Das, P.K., 2014. "A review of modern advances in analyses and applications of single-phase natural circulation loop in nuclear thermal hydraulics". *Nuclear Engineering and Design*, Vol. 280, pp. 326–348.

Creveling, H., Paz, J.D., Baladi, J. and Schoenhals, R., 1975. "Stability characteristics of a single-phase free convection loop". *Journal of Fluid Mechanics*, Vol. 67, pp. 65–84.

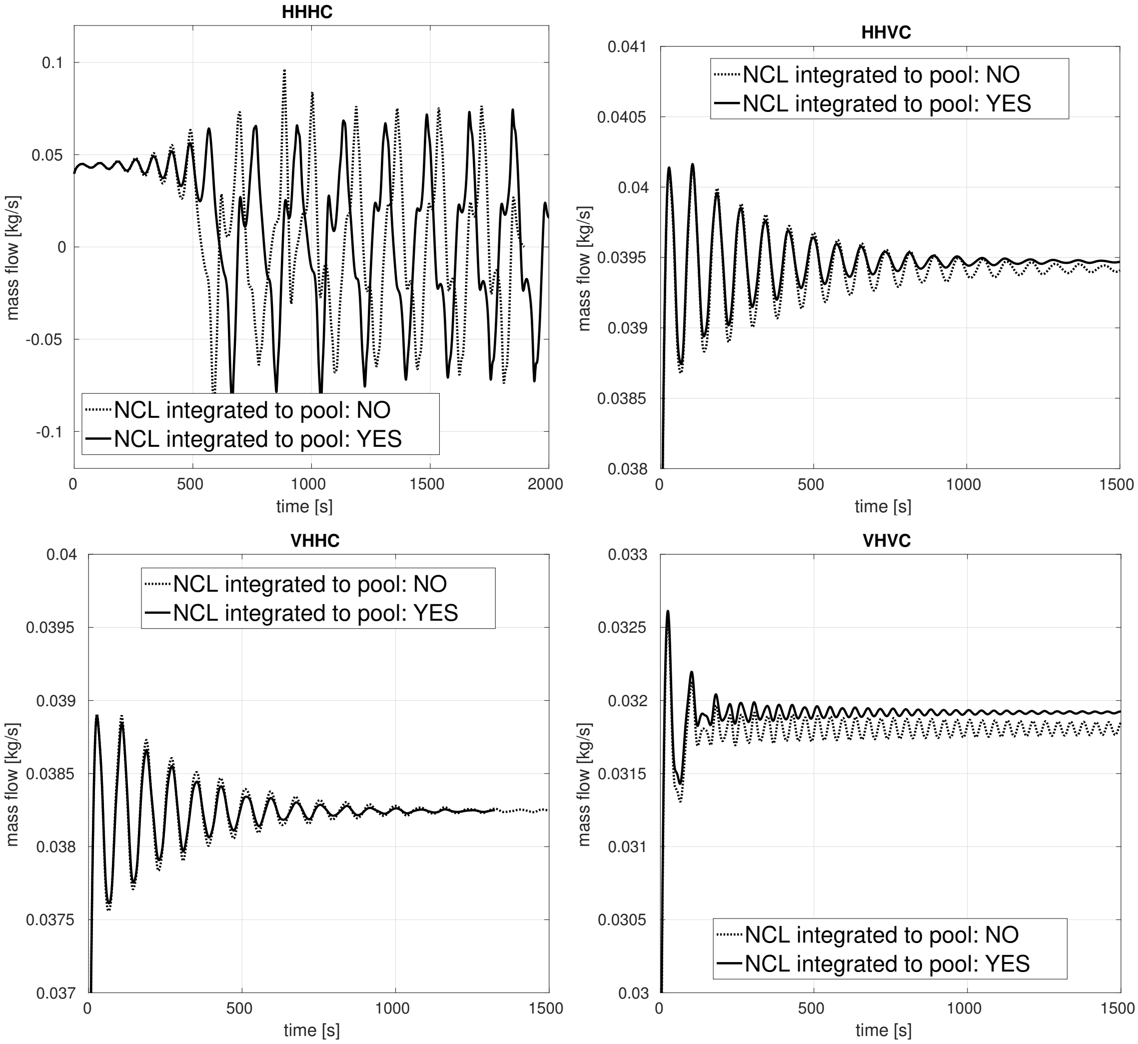

Figure 2. Transient results for the four configurations with heat input of 600 W. External (air) temperature is 30°C.

Keller, J.B., 1966. "Periodic oscillations in a model of thermal convection". *Journal of Fluid Mechanics*, Vol. 26, pp. 599–606.

Lima, L., Mangiavacchi, N. and Ferrari, L., 2017. "Stability analysis of passive cooling systems for nuclear spent fuel pool". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 39, pp. 1019–1031.

Pilkhwal, D.S., Ambrosini, W., Forgione, N., Vijayan, P.K., Saha, D. and Ferreri, J.C., 2007. "Analysis of the unstable behaviour of a single-phase natural circulation loop with one-dimensional and computational fluid-dynamic models". *Annals of Nuclear Energy*, Vol. 34, pp. 339–355.

Ruiz, D.E., Cammi, A. and Luzzi, L., 2015. "Dynamic stability of natural circulation loops for single-phase fluids with internal heat generation". *Chemical Engineering Science*, Vol. 126, pp. 573–583.

Shah, M.M., 2014. "Methods for calculation of evaporation from swimming pools and other water surfaces". *ASHRAE Transactions*, Vol. 120, part 2.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.