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Review

Experimental study on the influence of power steps on the thermohydraulic behavior of a natural circulation loop

M. Misale

DIME – Department of Mechanics, Energetics, Management and Transportation, Thermal Engineering and Environmental Conditioning Division, University of Genoa, Via All'Opera Pia 15-A, (I) 16145 Genova, Italy

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ABSTRACT

Single phase natural circulation is a heat transfer mechanism of great interest in various energy systems, including solar heaters, nuclear reactors, geothermal power production, engine and computer cooling.

The present paper deals with an experimental study on the influence of power steps on the behavior of a single-phase natural circulation loop. In particular two sets of experiments were performed: constant power and variable power. Several parameters such as the amplitude of power steps as well as the period of the oscillations were experimentally investigated.

The runs at constant power were carried out at different power levels from 500 W to 3000 W.

The experiments at variable power were carried out for the values of 500 W, 1000 W, and 2000 W. The amplitude of steps was ±50% or ±20% of the input power, whereas the period of the oscillations varied between 50 s and 7200 s.

All tests, both at constant power and variable power, show always an unstable behavior, i.e., temperature oscillations across the heated sections occur in the fluid. Moreover, the amplitude and the frequency of the oscillations increase as the input power increases. The thermal inertia of the loop plays a role in case of smaller time steps.

Contents

1. Introduction

The principal characteristic of the natural circulation process (*thermosyphon*) is that buoyancy forces due to the density gradient of the fluid drive the fluid flow in the vertical components of the system. Even though the forced convection is a more efficient heat transfer process than natural circulation, the latter methodology does not require the use of any moving part (pump), and can be preferred in all engineering applications in which the reliability must be guarantied. Therefore the natural circulation loops are extensively used in energy conversion systems, like solar heaters and cooling system of nuclear reactors, as well as in many other industrial fields, such as geothermal power production, turbine blade cooling, engine and computer cooling.

E-mail address: mario.misale@unige.it

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Nomenclature

D	internal diameter, mm
f	frequency, Hz
L	length, mm
P	power, W
T	temperature, °C

Greek symbols

$\Delta\tau$	time step, s
ΔT	temperature difference, K

Subscripts and superscripts

amb	ambient
avg	average
B-L	bottom left
B-R	bottom right
max	maximum
min	minimum
t	total

At least three thermal hydraulic behaviors could appear in a single-phase natural circulation loop: stable (invariant temperature difference across the heat sinks), neutral (oscillations of the temperature differences across the heat sinks without amplification), and unstable (amplification of the oscillations of the temperature differences across the heat sinks and flow reversals). In particular, in this paper, this last behavior was experimentally investigated. As well known, the instability in the loop depends on the interaction between the buoyancy force generated by density gradients and the frictional force along the loop [1].

Several experimental and theoretical works are available in the literature dealing with the physics of the flow and how it influences the heat transfer in themosyphons. In particular, thermosyphonic flows in the most common geometries and their applications are reviewed in [2–5]. In the case of closed and open rectangular loops, particular attention has been devoted to transient, steady state, as well as to stability analysis of the system under various heating and cooling modes.

Vijayan et al. [6] analyzed, experimentally and theoretically, the effect of loop diameter on the stability of single-phase natural circulation in rectangular loops. Three loops characterized by different internal diameter (D = 6 mm, 11 mm, and 23.2 mm) for the same total length were investigated. Using the linear stability analysis, a map able to predict the behavior of the loop was proposed and it can to take into account the ratio between the total length over the loop diameter. In particular, the unstable behavior was observed for low values of this ratio.

Nishihara [7] performed an analytical and experimental studies on an oscillatory instability of a single-phase natural circulation loop, showing that the instabilities are caused by enthalpy waves advanced by mean flow velocity along the loop.

Misale et al. [8], utilizing either distilled water or Fluorinert™ FC-43 in a rectangular loop showed the presence of two different power thresholds above which the loop behavior becomes unstable; moreover, the Fast Fourier Transform was applied to analyze the frequency of the oscillations [9,10]. The Relap5/Mod3.2 and Cathare2 V1.3u codes have been used, having both purposes of code assessment and interpretation of experimental data [11]. The simulations performed, however, showed the deficiency of the actual system thermal–hydraulic codes in predicting the instability (time and period of the flow reversals) of a single-phase natural circulation loop having simple geometry. Probably the discrepancies observed can be related to multi-dimensional effects, identified and characterized during the experiments performed to validate the two codes.

Suda [12] developed an experimental and numerical study on steady state, transient, and stability behavior of a vertical rectangular natural circulation loop. Various temperature oscillation patterns were measured and unstable and chaotic behavior was observed.

The occurrence of a chaotic behavior was analyzed by means the Lorenz's model both by Cammarata et al. [13] for two rectangular natural circulation loops and by Wang et al. [14] for a toroidal loop. Both studies show how the Lorenz's model can be applied, with good results, to the natural circulation loops.

In all the papers reported above the influence of the heat power was not investigated because all the experiments as well as simulations were performed at constant heat power [15,16].

Only recently, the researchers attention was focused on the case of not constant input power.

Rao et al. [17] studied the dynamic performance of a natural circulation loop with end exchangers under different power excitations such as step, ramp, exponential, and sinusoidal. They found that the natural circulation loop performance, expressed in term of maximum and minimum values temperatures were equal in all the cases except for the sinusoidal excitation. For the latter, as the frequency of the input excitation increases, the amplitude of response decreases and the delay time increases.

Basu et al. [18] analyzed numerically the influence of the modality to supply the heat power on the transient behavior in a natural circulation loop both increasing and decreasing the power. In particular, the authors studied the influence of different excitations of input power, i.e., step signal (instantaneous jump from the initial value to final one), ramp signal (linear transition over a specified period), exponential signal (decreasing gradient compared to the constant gradient of the ramp signal), and modified exponential signal (moderate increasing gradient). The simulation test started at a constant power of 1000 W and, after fixed time t_o, the power excitation was applied. In the case of step signal, the final power value was reached in a single step or in two steps varying the time between the first and the second step or in ten equal time steps. The ramp signal was applied considering two time values (500 s or 1000 s) to reach the final heat power. The same analysis was performed for the exponential signal and modified exponential signal. The final power input was reached after 500 s or 1000 s of power excitation. The authors showed that the input power excitation influenced the transient behavior as well as the stability of the thermo-hydraulic behavior of a natural circulation loop. In particular, ramp and modified exponential signals showed better performance than single/multiple steps or exponential signal. In fact, in the case of ramp and modified exponential signal, the mass flow rate oscillations were characterized by a lower amplitude increment than single/multiple steps or exponential signal, moving away the risk of flow reversal in the loop.

In this paper, the experimental results on the thermo-hydraulic behavior of a rectangular natural circulation single-phase rectangular loop are presented. In particular, the influence of the mode of power transfer to the fluid was investigated. Numerous experiments have been conducted adopting constant or variable input power. The latter experimental procedure was conducted varying