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Parallel connected natural circulation loops using different working fluids: experimental results

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Abstract. Natural Circulation Loops (NCLs) are closed-loop systems that transport heat from a source to a heat sink without a pump, relying on free convection of the working fluid. Previous research has focused on the stability and influence of different operative parameters on NCLs. This experimental study investigates the thermo-hydraulic performance of three parallel-connected NCLs with small inner diameters using three different working fluids: deionized water, glycol aqueous solution (50+50% wt), and FC-43 dielectric fluid. This study examines the steady-state behaviour of the NCLs at various heat sink temperatures and heat powers. The results indicate that the common one-dimensional model for a single loop's steady-state can be applied to this configuration and for all the tested fluids, and a proposed figure of merit can describe the working fluids and predict their steady-state behaviour.

1. Introduction

Natural circulation loops (NCLs) have been extensively studied due to their energy-efficient and cost-effective heat transfer capabilities. NCLs are closed-loop systems that use a working fluid that flows by free (natural) convection without the use of any external pumping system. The NCLSs have been used in various applications such as electronic cooling, solar panels, geothermic, and nuclear power plants.

The stability and influence of various operating parameters on NCLs have been extensively investigated in the past [1–4]. Analytical models have been proposed, including Vijayan's correlation, a simple formulation based on dimensionless numbers applicable to a single NCL [5]. Also numerical models have been used to study NCL behavior under various conditions, such as loop geometry (pipe diameter, length) [6], fluid properties [7], pressure losses[8], power steps or harmonic power excitation [9], Recently, complex loop configurations, such as series-connected [10,11] and parallel-connected loops [12], have also been studied numerically and experimentally. It has been found that even small inner-diameter loops are stable, even in parallel-connected configurations.

This work presents an experimental investigation of the thermo-hydraulic performance of parallel-connected NCLs with different working fluids. The study was conducted on a complex circuit consisting of three parallel-connected single-phase NCLs of small inner diameter, and the thermo-hydraulic performance at the steady-state was studied at different heat sink temperatures and heat powers. Three different fluids were tested: DI water, Glycol aqueous solution, and the dielectric fluid FC-43. The experimental setup and procedures are detailed in the following sections, and the results are analyzed and presented in the third section. This study aims to contribute to understanding the thermo-hydraulic behavior of parallel-connected NCLs with different working fluids and provide insights into their potential applications.

2. Methods

This section presents the experimental setup and procedures used to investigate the thermal-hydraulic behavior of different working fluids in three parallel connected natural circulation loops (NCLs). The study aimed to compare the performance of three fluids: DI water, Glycol aqueous solution, and FC-43, under different heat inputs and cooling conditions. The NCLs were constructed in a horizontal heater-horizontal cooler (HHHC) configuration, and the heat sink temperature was imposed using a cryostat. The experimental procedures involved measuring the temperature distribution along each loop, varying the heat power, and repeating the process at different heat sink temperatures. Additionally, one variable loop was used to study the mutual influence of the connected loops. The results obtained from this study are expected to provide valuable insights into the thermal-hydraulic behavior of natural circulation loops and aid in selecting the most appropriate working fluid for different applications.

2.1. Experimental setup

An experimental setup, represented in figure 1, consisting of three parallel connected NCLs, was used to measure the thermal-hydraulic behavior of various working fluids: DW Distilled Water ($Pr_{20°C} = 7.0$), aqueous Glycol solution ($Pr_{20°C} = 50.9$), and FC-43 ($Pr_{20°C} = 105.7$). The circuit was constructed in a Horizontal Heater-Horizontal Cooler (HHHC) configuration. Each loop has an independent heater localized in the lower part of the circuit, and its power can be adjusted (the maximum power value was selected to avoid possible phase changes in the working fluid). The heat sink temperature is imposed using a cryostat. The loop was thermally isolated using several layers of a composite isolation material to reduce the heat exchange with the ambient. The temperature was measured at different points along each loop using T-type thermocouples (0.5 mm OD), and the data was stored by a data acquisition system (estimated uncertainty of ± 1.0 K).

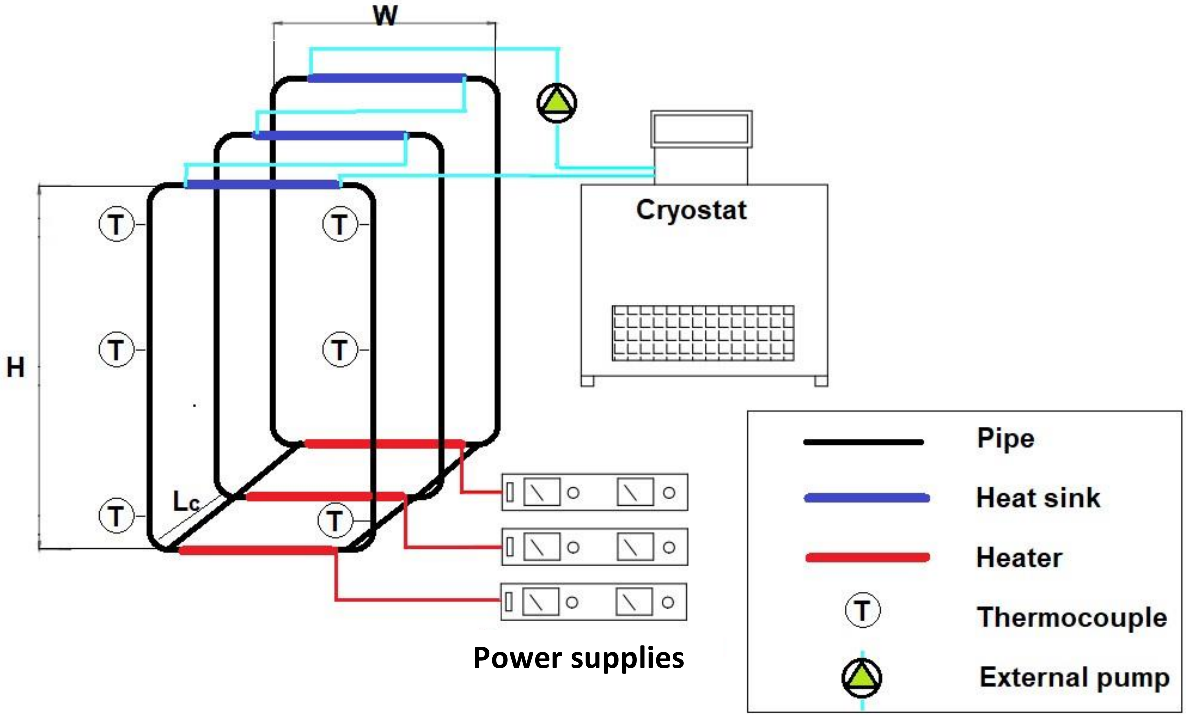

Figure 1. Sketch of the experimental setup.

2.2. *Tested fluids*

This section introduces the three fluids tested in the experiment: Distilled water (DW), Glycol aqueous solution (Glycol-water, 50%+50% wt), and FC-43 dielectric fluid with their properties and characteristics. DW water is a highly purified water commonly used in industrial applications due to its high purity and low conductivity. Glycol aqueous solutions are mixtures of water and glycol, typically used as coolants in HVAC systems and as antifreeze in automobile engines. FC-43 dielectric fluid is a fluorocarbon-based fluid with a low boiling point, low viscosity, and good chemical stability, making it suitable for high-performance cooling systems. The thermophysical properties of the fluids during the experiment were calculated using temperature correlations [13–15]. Table 1 presents the corresponding range of values (calculated during the experiments) for each physical property, including density (ρ), thermal conductivity (k), specific heat (c_p), thermal expansion coefficient (β), cinematic viscosity (γ), and Prandtl number (Pr).

Table 1. Fluid properties.

	Glycol-water	**FC-43**	**DW water**
ρ, kg m^{-3}	1102.0 - 1125.2	1778.5 – 1860.2	989.2 – 999.4
k, Wm^{-1}K^{-1}	0.413 - 0.434	0.063 – 0.065	0.585 – 0.632
c_p JK^{-1} kg^{-1}	3446 - 3640	1052 - 1110	4181 – 4185
β, K^{-1}	0.000490 - 0.000499	0.001172 – 0.001226	0.000128 – 0.000438
γ, m^2/s	1.63 10^{-6} – 5.51 10^{-6}	7.46 10^{-7} – 3.03 10^{-6}	5.80 10^{-7} – 1.20 10^{-6}
Pr, -	15.0 – 51.8	23.5 – 90.8	3.8 – 8.6

2.3. *Experimental procedures*

Two experimental procedures were employed during the experiments: Procedure A (single loop characterization) measures the temperature distribution along each loop, varying the provided heat power q from 20 W to 120 W (with 20 W steps). This procedure was implemented with every single loop working independently (disconnected from neighbor loops); Procedure B, one variable loop operates at different powers, and the neighbor loops remain at a fixed heat power (40 W). Procedure B was used to study the mutual influence of the connected loops. The experimental procedure was repeated at different heat sink temperatures.

3. Results

The temperature of each adiabatic vertical leg was obtained as an average of the three thermocouples positioned in each vertical section. The thermophysical behavior at steady-state was studied for the different fluids using ΔT_{avg}, the temperature difference between the adiabatic vertical legs of each NCL. It is possible to show that this temperature difference determines the mass flow rate of the working fluid. Moreover, as shown in Eq. (1), this temperature difference is proportional to the main operational parameters (in the first square root) and the figure of merit (FOM, that resumes the thermophysical properties of the working fluid). In Eq. (1), the gravity is g, the power q, the total loop length L, the loop height H, the diameter D, modified Grashof number Gr_m, and the geometrical factor N_G. The experimental results presented in figure 2 corroborate the dependency expressed in Eq. (1) for procedures A and B. Note that by increasing the power the first factor in Eq. (1) increases, however, the average temperature increases, which determines a smaller FOM (figure of merit) and therefore a negative effect on ΔT_{avg}.

$$\Delta T_{avg} = \sqrt{\frac{128\, q\, L}{\pi\, H\, D^4\, g}} \sqrt{\frac{k\, Pr}{{c_p}^2 \rho^2 \beta}} = \sqrt{\frac{Gr_m}{N_G}}\, FOM \tag{1}$$

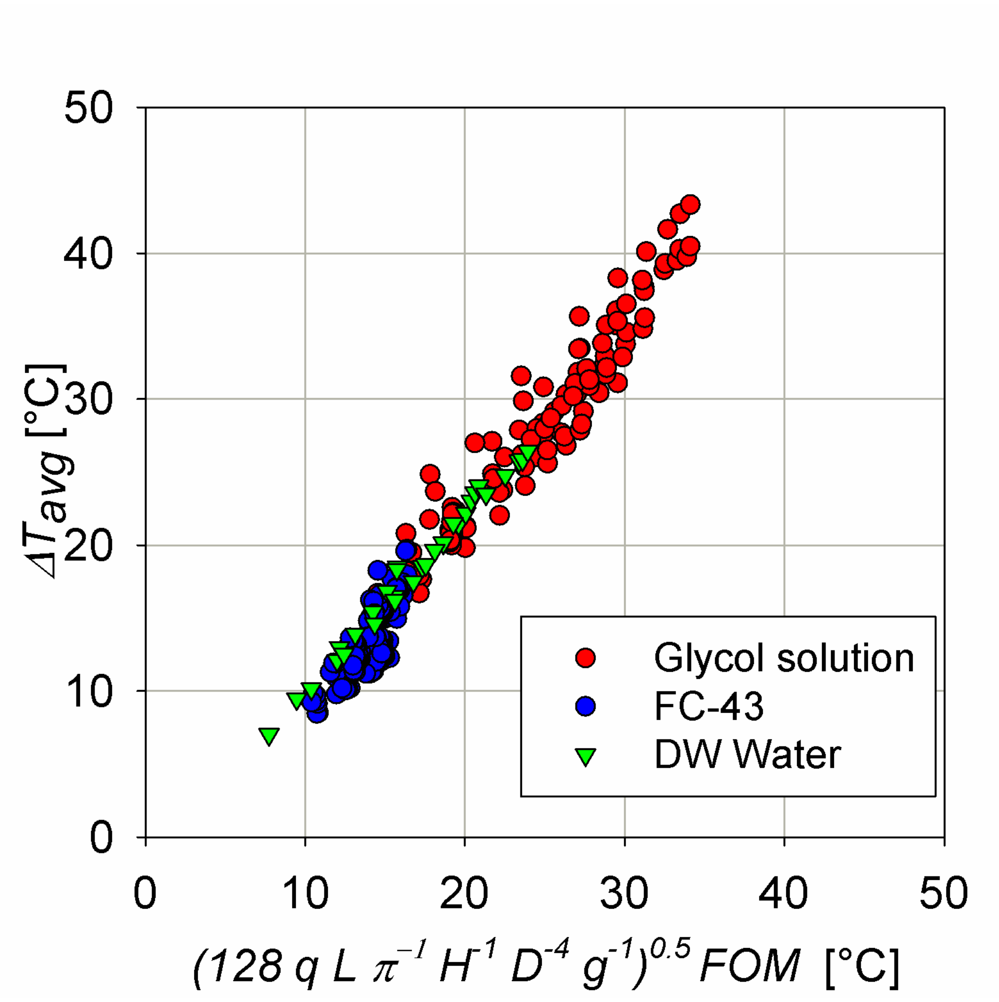

Figure 2. Experimental results: (a) relationship between the figure of merit FOM and ΔT_{avg}, Eq. (1).

Additionally, we corroborate Vijayan's correlation, Eq. (2), commonly used to describe the thermohydraulic behavior of a single NCL at the steady-state [5], see figure 2. This correlation links the Reynolds number at steady-state Re_{ss} with the fraction Gr_m/N_G (Gr_m represents the modified Grashof number and N_G a dimensionless geometrical parameter related with the friction factor).

$$Re_{ss} = 0.1768\sqrt{\frac{Gr_m}{N_G}} \tag{2}$$

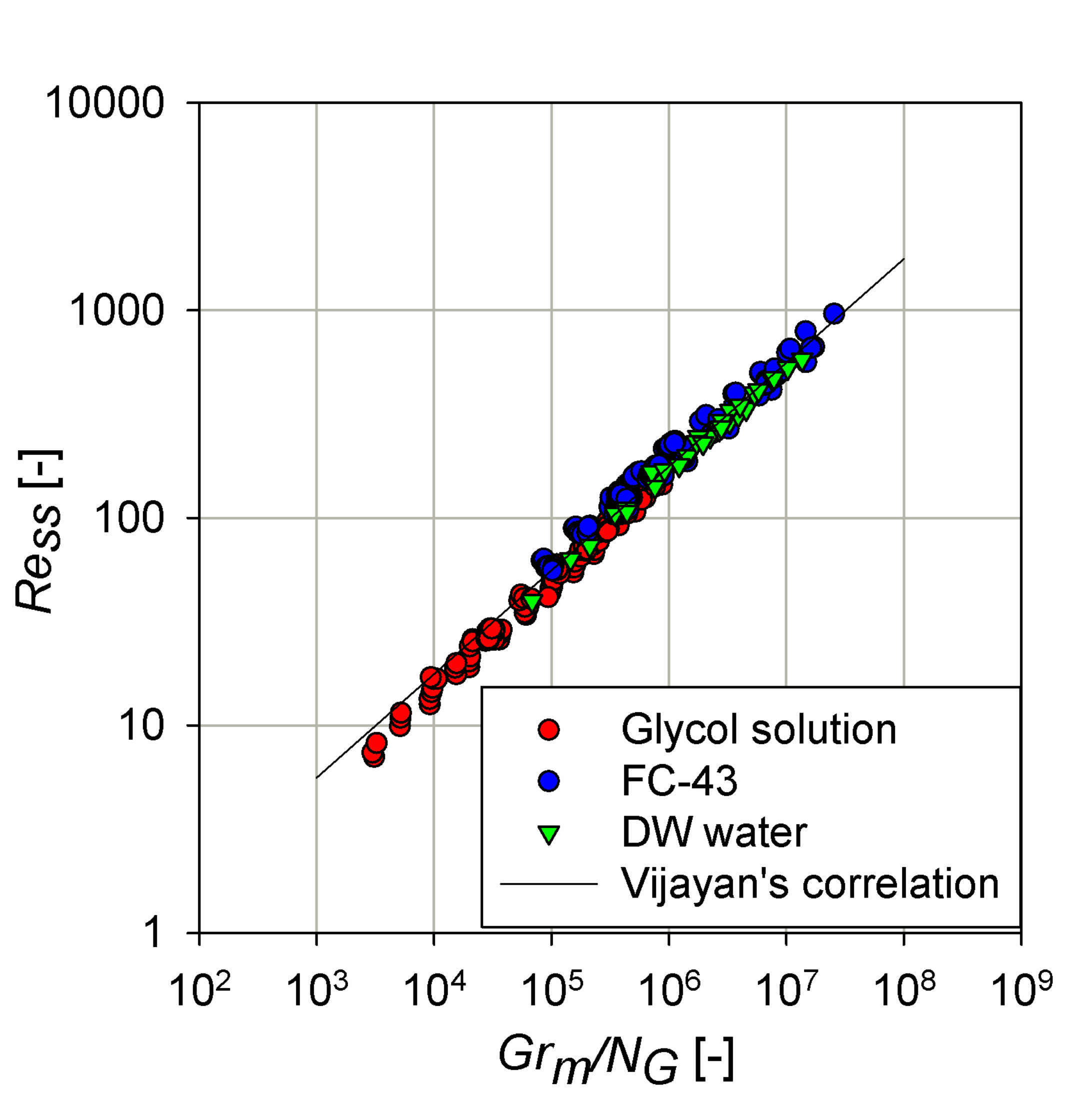

Figure 3. Relationship between dimensionless groups representing the thermo-hydraulic behavior of the parallel-connected loops at steady-state, comparison with Vijayan's correlation Eq. (2).

The results of Procedure B show that the neighboring loops' operating conditions slightly influence each neighbor loop's performance. For example, increasing the heat power in one loop can cause a decrease in the steady-state Reynolds number and thermal performance of the adjacent loops. However, the mutual influence is small and both equations, Eq. (1) and (2), correctly describes the behaviour of each NCL even when the power in one loop is changed by successive steps.

The results of this study demonstrate that the thermal-hydraulic behaviour of different working fluids can vary significantly depending on the operating conditions and the characteristics of the fluid. However, the same correlations apply to the circuits under the two experimental procedures, A and B. The data presented in this section can inform about the selection and design of heat transfer systems in various industrial applications. In future work, it may be useful to explore the behaviour of these fluids during transients, varying other parameters (such as NCL inclination's angle), and in more complex geometrical configurations. This will help further to refine our understanding of their thermal and hydraulic properties.

4. Conclusions

This study investigated the thermal-hydraulic behavior of three different working fluids: DW water, aqueous glycol solution, and FC-43, in parallel-coupled natural circulation loops (horizontal heater-horizontal cooler configuration). The results showed that the thermal performance of the NCLs is greatly affected by the properties of the working fluid and that the NCLs can provide effective cooling for a wide range of heat loads.

Overall, the obtained results indicate that the one-dimensional analytical model can describe the thermo-hydraulic behavior of the parallel-connected natural circulation loops for all the tested fluids. The analytical model was originally constructed for a single loop; however, the mutual influence is almost negligible for this complex NCL circuit (small inner diameter, parallel connected, different working fluids), and the analytical model is also applicable.

Our research has underlined the importance of selecting a proper working fluid to obtain the desired power range of operation. The figure of merit FOM represents a convenient way to synthesize the thermophysical properties of the working fluid; for example, the higher FOM values of the Glycol solution compared to DW water imply an operation at higher temperature differences and lower Reynolds numbers.

The findings of this study suggest that to fully understand the thermal performance of NCLs, future research should consider not only the steady-state behavior, but also the effects of the working fluid on transient behavior. A more comprehensive understanding of these dynamics will be crucial for developing more efficient and reliable NCLs in various industrial applications.

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