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Research paper

Experimental investigations and modeling of a loop thermosyphon for cooling with zero electrical consumption

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HIGHLIGHTS

- Modeling of thermosyphon loop for cooling telecommunication cabinet.
- The cooling system operates with zero electrical consumption.
- The new correlations are proposed for condensation and evaporation heat transfer.
- FOM equation is defined for selecting the best working fluid.
- The proposed model well predicts the experimental data and operating temperature.

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ABSTRACT

This paper presents an analytical model for a thermosyphon loop developed for cooling air inside a telecommunication cabinet. The proposed model is based on the combination of thermal and hydraulic management of two-phase flow in the loop. Experimental tests on a closed thermosyphon loop are conducted with different working fluids that could be used for electronic cooling. Correlations for condensation and evaporation heat transfer in the thermosyphon loop are proposed. They are used in the model to calculate condenser and evaporator thermal resistances in order to predict the cabinet operating temperature, the loop's mass flow rate and pressure drops. Furthermore, various figures of merit proposed in the previous works are evaluated in order to be used for selection of the best loop's working fluid. The comparative studies show that the present model well predicts the experimental data. The mean deviation between the predictions of the theoretical model with the measurements for operating temperature is about 6%. Besides, the model is used to define an optimal liquid and vapor lines diameters and the effect of the ambient temperature on the fluid's mass flow rate and pressure drop.

1. Introduction

Energy consumption is a major operating cost in the telecommunication field where 33% of electricity is used for cooling. Consequently, a large variety of cooling systems have been studied to maintain an applicable temperatures for telecommunication equipment. Active cooling systems need complex air filtration designs and high cost maintenance. They do not match the demand from the systems with a high thermal dissipation. As stated by Oliveira et al. [1], air cooling systems are disadvantaged by acoustic noise generation, electrical power consumption, weight addition, and periodic maintenance requirements. Passive cooling systems arose as an innovative solution due to their ability of withstanding high heat fluxes with low working fluid charge, controlling system temperature automatically, and working with a minimum energy consumption and a less noise. They hold better thermal performances than active and semi-active systems because they use phase change processes providing higher heat transfer coefficient at low mass flow rates. They offer various advantages such: (i) ability of dissipating heat from a heat source to a heat sink over a relatively long distance, (ii) no moving parts leading to a more reliable system operation, (iii) greater flexibility while choosing working fluids compatible with telecommunication equipment, (iv) reduction in the working fluid fill charge, and (v) and zero electrical consumption.

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Passive loop has been broadly studied since it interferes in the industrial cycle like the cooling of gas turbine blades, electrical machine rotors and transformers, nuclear reactors, steam tube for baker's oven, internal combustion engines, and electronic devices. Li et al. [2] carried out experiments on a unique insert-type two-phase closed thermosyphon loop that would assist in reducing cost, installation difficulty, and maintenance for solar water heaters. Sarno et al. [3] studied a thermosyphon loop for cooling a seat electronic box in avionics application. They showed that the loop integration allows to double the seat electronic box cooling capability. Tsoi et al. [4] examined thermal performance of a devised plate-type thermosyphon loop assigned for telecommunication systems electronic boards cooling. They studied free and forced convective cooling conditions for both horizontal and vertical orientations. Sundaram et al. [5] investigated the telecom shelters cooling using a combination of a phase change materials and a thermosyphon loop. They showed that the use of a passive cooling system makes the telecom shelter as a green shelter because 14 tons of carbon footprints could be saved every year. Sun et al. [6] proposed a new cooling technology combining phase change material with a natural cold source for telecommunication base stations. Based on their results, the estimated average energy savings potential is 50%. Kim et al. [7] proposed a new design of loop thermosyphon for the cooling B-ISDN telecommunications system. Water, acetone, ethanol, RII, RI13, FC-72 and FC-87 had been used as the working fluids. Samba et al. [8] conducted an experimental investigation on a small telecommunication cabinet cooled by a loop thermosyphon using fans on the condenser and evaporator. They used n-pentane as a working fluid and found that heat load could be extended to 3 times that the limit obtained by convective air cooling.

However, modeling of thermosyphon loop cooling air flow inside a telecommunication cabinet has not been deeply investigated. Zimmermann and Melo [9] investigated a carbon dioxide loop thermosyphon designed to fulfill the geometric and temperature requirements of a specific free piston Stirling cooler. A mathematical model was also developed to study influence of the refrigerant charge and connecting lines diameter. Huminic and Huminic [10] developed a numerical model to investigate volume concentration of nanoparticles in the working fluid on thermal performance of a thermosyphon loop. Khodabandeh [11] conducted a theoretical investigation on a thermosyphon loop where six correlations for calculating the gravitational pressure drop were combined with four frictional pressure drop correlation's. He found that the homogeneous model gives most accurate predictions of the experimental results. Garrity et al. [12] investigated the quasi-steady behavior of a thermosyphon loop to obtain a quantitative understanding of the onset of unstable flow phenomenon observed at large heat fluxes. The one-dimensional momentum equation based model had been presented to provide a framework for the instability onset prediction. Moreover, Metcalf et al. [13] proposed an analytical approach to modeling a thermosyphon loop. Their model used mass, momentum, and energy balances to predict the vapor quality, mass flow rate, and pressure drop around the loop.

This work focuses on the modeling of heat and mass transfer in a thermosyphon loop used as a cooling system for a hot air flow inside a telecommunication cabinet. A theoretical model is developed to predict the mass flow rate, pressure drop, operating temperature, and thermal efficiency of thermosyphon loop under various operating conditions. Tests are conducted in order to determine correlations for loop thermosyphon's condensation and evaporation heat transfer coefficients. Various working fluids are tested in order to highlight their effects on the cooling loop efficiency. Besides, several simulated conditions results are presented, analyzed, and compared.

2. Experimental setup

Actually, Orange telecommunication cabinets use fans as a cooling system through circulation of cabinet internal air. For different heat load, Fig. 1 shows the system thermal resistance (R_{sys}) which is used as an index of cooling technologies performance. R_{sys} is determined as

$$\boldsymbol{R_{sys}} = (\boldsymbol{T_{op}} - \boldsymbol{T_{amb}})/\boldsymbol{Q_{in}} \tag{1}$$

where T_{op} is the operating temperature measured in the cabinet, T_{amb} is the ambient temperature, and Q_{in} is the heat load.

The maximum system thermal resistance is determined for an operating temperature given by the ETSI [14] standard. As shown by Fig. 1, the maximum heat load is limited to 250 W using only the traditional cooling system. The heat generated inside the cabinet is trapped there. Using a passive loop, heat could be evacuated from the cabinet to another separated heat sink. This cooling system is an appropriate solution because it is an energy-transfer device capable of transferring heat from the cabinet to its condenser heat sink neatly without any contaminants entering the enclosure (as shown by Fig. 2).

Fig. 3a shows the studied cabinet prototype and the cooling thermosyphon loop assembly. The telecommunication equipment boxes are located at the cabinet center with an adjusted heat using a voltage autotransformer. The thermosyphon loop consists of an evaporator connected to a condenser by the means of two stainless steel tubes. The loop's evaporator is installed inside the cabinet unlike its condenser, which is located behind the cabinet. Heat generated inside the cabinet could be dissipated by evaporation of the working fluid in the evaporator. The arriving vapor at the condenser changes into liquid under the effect of natural convection at the condenser external surfaces. After that, condensate flow leaving condenser moves under gravity along the liquid line.

The evaporator is fabricated from a high thermal conductivity copper block. It is composed of two compensation chambers for the liquid and vapor working fluid separated by a microchannels block. The liquid chamber is located at the bottom of the micro-channels zone in order to recover condensate from the condenser, while the vapor chamber is located at the top of the micro-channels zone. The evaporator is fitted with micro-fins for improving heat transfer. The condenser consists of a copper tube coated by rectangular thin fins placed through the tubes length and cooled by natural air

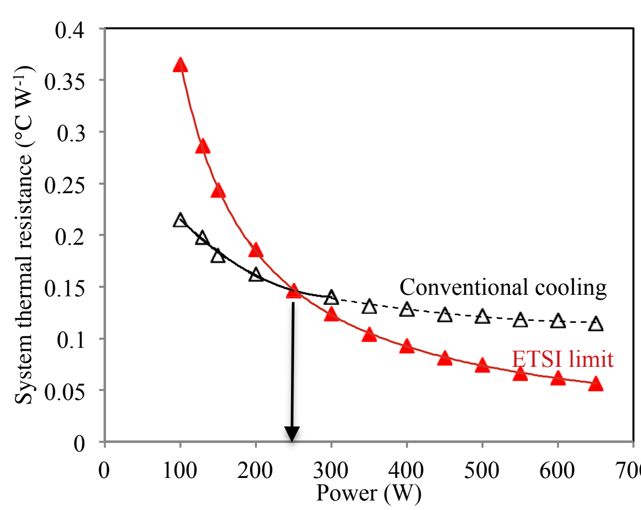

Fig. 1. Orange telecommunication cabinet prototype performance limit using traditional cooling.