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Advanced multi-evaporator loop thermosyphon

M. Mameli [a, *], D. Mangini [b], G.F.T. Vanoli [c], L. Araneo [c], S. Filippeschi [a], M. Marengo [b, d]

[a] Università di Pisa, DESTEC, Largo Lazzarino 2, 56122, Pisa, Italy
[b] Università di Bergamo, Viale Marconi 5, 24044, Dalmine, BG, Italy
[c] Politecnico di Milano, Dipartimento di Energia, Via Lambruschini 4A, 20158, Milano, Italy
[d] University of Brighton, School of Computing, Engineering and Mathematics, Lewes Road, Brighton, BN2 4GJ, UK

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ABSTRACT

A novel prototype of multi-evaporator closed loop thermosyphon is designed and tested at different heaters position, inclinations and heat input levels, in order to prove that a peculiar arrangement of multiple heaters may be used in order to enhance the flow motion and consequently the thermal performance. The device consists in an aluminum tube (Inner/Outer tube diameter 3.0 mm/5.0 mm), bent into a planar serpentine with five U-turns and partially filled with FC-72, 50% vol. The evaporator zone is equipped with five heated patches (one for each U-turn) in series with respect to the flow path. In the first arrangement, heaters are wrapped on each bend symmetrically, while in the second layout heaters are located on the branch just above the U-turn, non-symmetrical with respect to the gravity direction, in order to promote the fluid circulation in a preferential direction. The condenser zone is cooled by forced air and equipped with a 50 mm transparent section for the flow pattern visualization. The non-symmetrical heater arrangement effectively promotes a stable fluid circulation and a reliable operation for a wider range of heat input levels and orientations with respect to the symmetrical case. In vertical position, the heat flux dissipation exceeds the pool boiling heat transfer limit for FC-72 by 75% and the tube wall temperatures in the evaporator zone are kept lower than 80 °C. Furthermore, the heat flux capability is up to five times larger with respect to the other existing wickless heat pipe technologies demonstrating the attractiveness of the new concept for electronic cooling thermal management.

1. Introduction

According to the more optimistic scenario (Representative Concentration Pathway 2.6) expected by the Intergovernmental Panel on Climate Changes [1], an average 50% reduction of greenhouse emissions is required by 2050, relative to 1990 levels, in order to obtain their substantial decline thereafter. The energy consumption and the efficiency of several industrial processes are nowadays under the magnifying glass. For instance, recent studies on information technology data centers showed that the rate of increase of their energy consumption is growing faster than several other major industries [2]. In particular, due to the miniaturization of electronic components and the consequent increase of power densities, the electric energy required for electronic thermal management contributes to a large amount with respect to the total (up to 50% for data centers) Indeed, heat dissipation is mainly achieved through active systems, such as forced convection liquid loops or fans above the heat sinks directly mounted on the boards. In this context, the implementation of passive two-phase heat transfer devices would be a breakthrough solution: being very efficient heat flux spreaders, two-phase passive devices are capable of reducing the very high heat powers per unit of surface generated by the electronics in contact with the evaporator, to the lower heat fluxes that may be dissipated on larger and more accessible surfaces in the condenser zone. This allows to substantially reduce the fan energy consumption in the case of optimized natural or mixed convection coolers.

Two-phase heat transfer loops have always been attractive for their compactness, high performance and because they are thermally driven. While the last decades witnessed the overwhelming spread of the heat pipe technology under various forms such as grooved and sintered heat pipes, loop heat pipes and capillary pumped loops, the interest in wickless, gravity driven technologies, namely the Two-Phase Thermo-Syphons (TPTS), never damped out. The capability to transport heat at high rates over appreciable distances, without any requirement for external pumping devices,

* Corresponding author.
E-mail address: mauro.mameli@ing.unipi.it (M. Mameli).

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the low cost, durability and relatively simpler modeling/design process make this technology very attractive for many thermal management applications. Indeed, TPTS have been investigated in plenty of fields such as: nuclear plants [3], energy systems [4], solar heat recovery [5–7], air conditioning [8], electronic cooling in avionics [9] and in railway traction [10]. The typical TPTS [11] consists of a single envelope where the heat-receiving (evaporator) zone is usually filled with the liquid phase and it is located below the heat rejecting (condenser) zone. As the evaporator zone is heated up, the liquid starts boiling and vapor rises and condenses on the walls in the heat-rejecting zone. The liquid film flows down the walls by gravity to the evaporator zone, counter-current the vapor. At high heating power input, because of the correspondingly large mass flow rate of the vapor, the liquid-vapor interfacial shear stress becomes increasingly relevant. Once the interfacial shear force overcomes the gravitational force on the liquid film, the liquid flow may be reversed and the flooding limit is reached. Many novel designs have been proposed to overcome the flooding limit, which include an internal physical barrier along the adiabatic section bypass line for liquid return, also known as a cross-over flow separator [12]. The main advantage of these designs is that the liquid and vapor flows have partially separated passages, which can result in a higher flooding-limited heat transfer capacity. Another possibility to separate phases and increase the device performance is to create a closed circuit. In such a loop, the fluid is forced to circulate in a preferential direction by the coupled effect of vapor pressure and gravitational force as thoroughly described by Ref. [13]. Thanks to the relatively small cross section with respect to the standard TPTS, the expanding vapor phase pushes batches of fluid (both liquid and vapor) towards the condenser section. In the cooled zone, vapor condenses and the tube is completely filled by the liquid phase that is driven back to the evaporator by gravity. This particular fluid flow motion is better known as "bubble lift" principle [14] and shown in Fig. 1. Defining the capillary length as $l_c = \sqrt{\sigma/g(\rho_l - \rho_v)}$, the looped TPTS based on the "bubble lift" concept fills the gap between the capillary dominated systems (Pulsating Heat Pipes $d < 2l_c$ [15,16]) and the buoyancy dominated systems (Counter-flow thermosyphons $d > 19l_c$ [14]).

In the present work, the concept of single closed loop thermosyphon is revolutionized in a twofold manner: first, the tube is bent in a serpentine manner introducing multiple heated and cooled zones; second, the heating patches are strategically switched from a symmetrical to a non-symmetrical layout in order to enhance the fluid flow circulation of in a preferential direction. This creates a novel device that might be named as Multi-Evaporator Loop Thermosyphon (MELT). Since the fluidic path is unique and the heated and cooled zones are in series, the present device works in a different way as the parallel assessments [17,18] previously studied in literature. In the same time, it doesn't lose its construction simplicity. The studied one in this paper consists of an aluminum tube, which is bent in a serpentine and partially filled with FC-72. Based on the current approach, this device represents a Multi-Evaporator Loop Thermosyphon (MELT). Experimental results show that the non-symmetrical location of the heated zones is beneficial with respect to the symmetrical both in terms of fluid circulation enhancement and heat flux removal. Thanks to the self-sustained fluid circulation, the maximum heat flux abundantly exceeds the standard pool boiling critical flux by up to 75%, and largely improves upon the heat input range capability of standard thermosyphons [19] and other promising wickless heat pipe technologies [20] operated with fluorinerts.

Table 1 resumes the advantages and drawbacks of the wickless heat pipe technologies according to some general merit parameters such as performance, cost, modeling. Despite the dependency on gravity assistance and the actual lack of design tools, the MELT technology represents a good alternative to the standard thermosiphon where more geometrical flexibility is needed and a good alternative to the Pulsating Heat Pipe where higher heat flux capability and compactness are requested.

2. Experimental set up and procedure

The proposed cooling device is made of an aluminum tube (Inner/Outer tube diameter 3.0 mm/5.0 mm) bent into a planar serpentine with five U-turns at the evaporator (curvature radius 7.5 mm) and ten parallel channels. Two "T" junctions, respectively devoted to the vacuum and filling procedures and fluid pressure measurement (Kulite®, XCQ-093, 1.7 bar Absolute), also allow to install a 50 mm glass tube for the purpose of visualization, as shown in Fig. 2a.

A low vapor-pressure glue (Varian Torr Seal®) seals together the aluminum tube, the "T" junctions and the glass tube. Sixteen "T" type thermocouples (bead diameter 0.2 mm, ± 0.3 K) are located on the thermosyphon external tube wall: ten in the evaporator zone and six in the condenser zone, while a PT 100 sensor (Class B sensor RS®) is utilized to measure the ambient temperature as illustrated

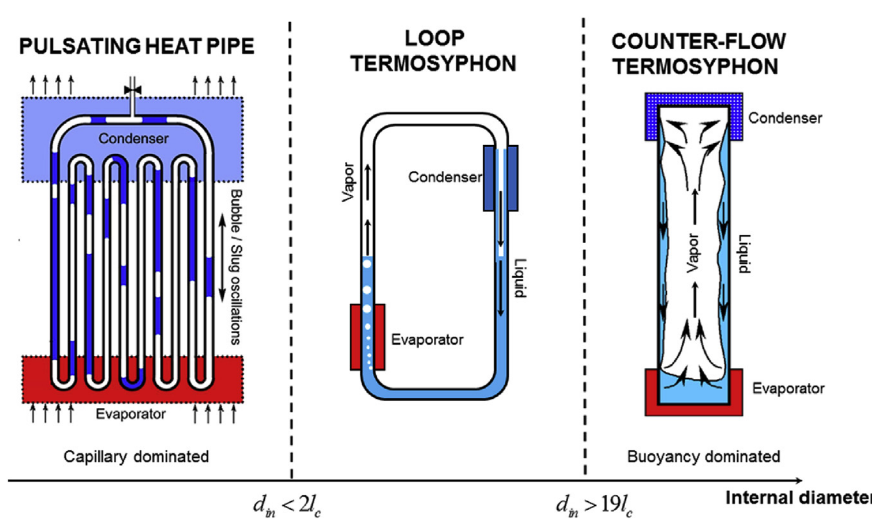

Fig. 1. Wickless Heat Pipes working principles in the light of the confinement criteria [14].