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Heat Pipe Reactors: a review of heat pipes in nuclear reactors and the role for small modular reactors and to space exploration

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1. Introduction

Heat Pipes (HPs) are components which had received new attention nowadays, becoming subject of intense research in areas such as nuclear and space exploration. This is mainly motivated due to its elevated capacity to move heat from a local to another without the inherent problems of complex systems and equipment such as pumps, compressors, pipes and valves, since they do not have any moving parts, making them especially suitable for standalone applications or those in which the access to maintenance, compactness, lower weight, or long-term operation are a concern [1, 2].
When used in applications involving nuclear reactors, these reactors are known as Heat Pipe Reactors (HPRs). Depending on the design, it is possible to transfer large amounts of heat without the typical issues related to the employ of liquid coolants (boil and transients such as LOCAs – Loss Of Coolant Accidents) while keeps the whole system more compact and lightweight when compared with Gas Cooled Reactors (GRs) and Light Water Reactors (LWRs) [1, 2].
With the recently renewed interest in space exploration for human establishment in the Moon and Mars, into shorten the duration of a space flight travel to neighbor planets and their moons as well as for deep space exploring by unmanned spacecrafts, the HPRs have gained, again, relevance since they comply with stringent requirements in this kind of application. One of most recent projects of spacecrafts using HPs is the KRUSTY, which is one kind of kilopower reactors series and which should receive new developments to its power reach the mega Watts of power [1].
On the other hand, the climate change has driven the development of several low carbon technologies, with the nuclear source appearing as one of the most important resource during the transition from a high-carbon to a low-carbon or decarbonized energy matrix once it does not emit Green House Gases (GHGs) during the power generation. In this context, developments such as the Small Modular Reactors (SMRs) had received great attention since allows to attend suitable the increasing energy demand, could generate power close to the densely populated regions and with elevated consumption without require that larger areas being occupied, longer construction time investments. Notwithstanding, the SMRs are still adequate for off-grid applications, being very attractive to attend humanitarian missions and emergencies once they could be compact and lightweight enough to be transported by rail, road, airplane or boat to these locals quickly. In this view, the SMRs requires a compact heat rejection system, which should be better achieved by using HPs [2].
In this work, a brief introduction of the main requirements for HPs thermal-fluid dynamics evaluation using a CFD (Computational Fluid Dynamics) code is presented. This would support the second step of

the research in which the CFD simulations would be performed aiming to better understand the governing phenomenon in HPs that would allow its development in future. These requirements are presented in section 2, Methodology, since they are prerequisites for the simulations starts.

2. Methodology

To simulate numerically the HPs using a CFD code, some data/information should be previously known/available. Depending on the CFD code used, specific data could be additionally required. In this manner, the prerequisites highlighted in this section refers to those that are most common. These data could be obtained in tables of thermophysical properties, papers, pages of manufactures and from experimental data [3, 4].

- Application: the knowledge of the application in which the HPs would be used is a prerequisite since it could provide a deep understand of the benefits and limitations of their use. In this case, two possible applications are sighted: spacecrafts/satellites and SMRs [1, 2];

- Type: each kind of application could have its need better fitted by some HPs types. To each case, a specific geometry is required to the HP operate properly while explores a specific phenomenon, which could be better described by a 2D or 3D approach. Some common types of HPs are using wick grooved or of porous material [3, 4];

- Geometry: this refers to external and internal shape of the HPs. Externally, two common shapes are cylindrical (the most usual) and triangular. Internally, there is the option to use a filling material for the wick or not and the most common types are: wick with fins grooved, wick with fins of a porous material and wick of porous material that fill in all the internal void of the HPs. Each of these types have specific dimensions to be modeled/constructed and have a better performance in one kind of application but not in another since they could operate based on different physical principles (thermosyphon, capillary, etc). In this manner, the geometrical parameters vary largely [3, 4]. Some of them are:
    - External dimensions and shape: vary according to the HP type. Some usual geometrical parameters are diameter, for the cylindrical shape, or each side length, for the triangular shape. Notwithstanding, HPs are divided in three sections, evaporator, condenser and adiabatic. In this manner, its modeling requires to know these dimensions since they affect the performance of the HPs [3, 4];
    - Internal dimensions: for HPs that have internal fins (grooved wick), it is also required: quantity and shape of fins (height, width, cross-section shape). For HPs with wicks in an annular shape is only required the internal diameter [3, 4];

- Material: the external structure of HPs serves not only for heat transfer purposes, but also for attach it to other components of the system. In general, it could be made of metals such as copper, aluminum, nickel alloys and stainless-steel since them have good heat transfer properties (as follows detailed) as well as strength to support loads. Internally, the materials could vary depending on the type of HP. For grooved type, it is usually the same of the external material since the grooves of the wick are manufactured in the sheet of metal curved or conformed as need. For those in which the wick is made of a porous material, the wick geometry is obtained by different process such as sintering. In any case, from the thermal-fluid dynamics point of view, it is required to know: morphology (physical state, solid/porous material), thermal conductivity, porosity, void fraction and permeability (as required for porous materials) [3, 4, 5];

- Working fluids: the suitable operation of HPs depends significantly on the working fluids properties. Some of them that are common required to characterization in a CFD code are: morphology (pure substance, mixture with constant/variable properties, etc), thermal conductivity, thermal expansion factor, saturation pressure and temperature, molar mass, specific thermal capacity (or specific heat), density, dynamic viscosity, reference values for the values adopted regarding the pressure, temperature, enthalpy and entropy [3, 4, 5];

3. Results and Discussion

The application of HPs within the nuclear sector is not new, having examples of spacecrafts that have being used them (in this case, an HPR), so a variation from a type of HP to another and its choice is based on the requisites of the mission such as weight, size, long-term duration and costs. On the other hand, for ground applications, there is a new potential use with SMRs since the HPs are compact enough and could deal with large amounts of heat without compromise its performance even when submitted to operational transients. Regarding the safety aspects, this feature is also important since it reduce the risk of accidents and could collaborate to diminish its gravity and consequences [1, 2].

Despite of its simplicity, it could be observed that its development and optimization require the knowledge of several characteristics, geometrical and physical from the materials used in its construction, for its operation and heat transfer as well as from the application. Considering that some works provides them, it is possible to design and simulate it in a CFD code for benchmark and validation purposes of the code, after which a parametric study could be performed aiming to find the optimal setup and compare it with the other geometries/kinds of HPs. This data survey is under course and is expected that a first validation simulation could be performed in next future [3, 4, 5].

4. Conclusions

In the view of the discussion presented, it could be concluded that the employ of HPs could overcome some limitations within applications involving nuclear reactors. Several data/information are required as prerequisites aiming to perform a numerical simulation that result in a set of values which could be evaluated pursuing a future optimization of a HP type. Despite of the large list of requisites, several information could be find easily and a next future, a first validation simulation is expected to be performed.

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References

[1] "Nuclear Reactors and Radioisotopes for Space". World Nuclear Association. https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-reactors-for-space.aspx (2021).

[2] "Small Nuclear Power Reactors". World Nuclear Association. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-

reactors.aspx (2021).

[3] CHEN, Y.; ZHANG, C.; SHI, M.; WU, J.; PETERSON, G.P.; "Study on flow and heat transfer characteristics of heat pipe with axial ''Ω"- shaped microgrooves". *International Journal of Heat and Mass Transfer*, vol. 52, pp. 636-643 (2009).

[4] ZHANG, C.; CHEN, Y.; SHI, M.; PETERSON, G.P.; "Optimization of heat pipe with axial ''Ω"-shaped micro grooves based on a niched Pareto genetic algorithm (NPGA)". *Applied Thermal Engineering*, vol. 29, pp. 3340-3345 (2009).

[5] ANSYS-CFX®, "User Guide CFX® Release 20.1". ANSYS®, 2020.