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Multiphase numerical analysis of heat pipe with different working fluids for solar applications

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Abstract: Energy crisis is a prognosis predicted in many cases with the indiscriminate encroachment of conventional energy sources for applications on a massive scale. This prediction, further emboldened by the marked surge in global average temperatures, attributed to climate change and global warming, the necessity to conserve the environment and explore alternate sources of energy is at an all-time high. Despite being among the lead candidates for such sources, solar energy is utilized far from its vast potential possibilities due to predominant economic constraints. Even while there is a growing need for solar panels at more affordable rates, the other options to harness better out of sun's energy is to optimize and improvise existing technology. One such technology is the heat pipe used in Evacuated Tube Collectors (ETC). The applications of heat pipe have been gaining momentum in various fields since its inception and substantial volumes of research have explored optimizing and improving the technology which is proving effective in heat recovery and heat transfer better than conventional systems. This paper carries out a computational analysis on a comparative simulation between two working fluids within heat pipe of same geometry. It further endeavors to study the multiphase transitions within the heat pipe. The work is carried out using ANSYS Fluent with inputs taken from solar data for the location of Vellore, Tamil Nadu. A wickless, gravity-assisted heat pipe (GAHP) is taken for the simulation. Water and ammonia are used as the working fluids for comparative multiphase analysis to arrive at the difference in heat transfer at the condenser section. It is demonstrated that a heat pipe ETC with ammonia as working fluid showed higher heat exchange (temperature difference) as against that of water as working fluid. The multiphase model taken aided in study of phase transitions within both cases and supported the result of ammonia as fluid being a better candidate.

1. Introduction

Solar energy is among the most potential candidates for green energy in the future. Harnessing of solar energy has been researched extensively for the past decades and is gaining momentum with advent of time. Between the two modes of energy, solar thermal power is becoming more and more attractive in places with high insolation, like India. This work endeavors to realize the necessity towards better, more efficient utilization of the available solar energy. Heat pipe as a solution for energy (heat) transfer, exchange or recovery is gaining

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momentum ever since its inception. It is a simple evaporation-condensation device with closed circulation of working fluid, usually of low latent heat of vaporization, that is exploited to evaporate the fluid by injection of heat at one inlet (namely, the evaporator section) and rejection of heat and subsequent return to original phase at an outlet (called the condenser section). Capillary action (enforced through wicks of various structures and designs) and/or body forces maintain the closed circulation within the heat pipe. Heat pipe is found to be of particularly extensive application in/with solar collectors. This work aims at comparative analysis of two working fluids within a heat pipe. The literature review was aimed towards learning the same. An overview on the application of heat pipe in renewable energy sector was encapsulated by HN Chaudhry et al [1]. Sameer Khandekar et al investigated [2] the effect of bulk forces within a heat pipe and laid out preliminary design procedures for pulsating heat pipes. Study on gravity-assisted heat pipe for thermal storage unit was done by Bo-Wen Hu et al [3] and Saeed Tiari et al [4] discussed on the application of heat pipe and the phase change involved in it to store and transport thermal energy. Shoeib Mahjoub and Ali Mahtabroshan worked on numerical simulation of a conventional heat pipe [5] from governing equations. MH Saber and M Mazaher Ashtiani studied a CFD model of heat pipe to evaluate and improvise the evaporator performance [6] which guided the authors' understanding of the design aspects of heat pipe. The work on heat transfer characteristics of a heat pipe of various wick structures across different working fluids by Naveen Kumar et al [7] was instrumental in understanding the effect of wicks in the system. Comprehensive investigations carried out by Ayompe et al elaborated on the economic advantages and the improved efficiency of an Evacuated Tube Collector (ETC) as against conventional solar flat plate collector [8], providing inspiration to selection of heat pipe ETC as the testing condition. The work on heat pipe ETC by S Hlaing [9] is taken for design considerations and parameters. An overview of computational analysis on GHAP is gathered from the work of Archit Deshpande et al [10] and Fadhl et al [11]. Across the literature, the authors found a prevalent trend of solutions performed for two separate entities of phases within the same heat pipe that shared a common interface as against the phenomenon of a dispersed phase that is observed. Our work applied a multiphase mixture model for computational analysis.

2. Computational model

Computational analysis is increasingly developing as the go-to approach towards studying and solving engineering problems. The approach involves the simulation of a model, adapting the appropriate boundary conditions and any numerical technique for solution.

Analysis is carried out on a two-dimensional segment of the vertical, wickless, gravity-assisted heat pipe (GAHP) with an evaporator, a condenser and adiabatic section. The solar flux taken at evaporator is calculated for Vellore (12.9165° N, 79.1325° E). Free stream temperature is taken at 25°C for February month. Table 1 shows the dimensions of the model taken.

Table 1. Dimensional parameters

S. No	Parameter	Dimension (in meters)
1	Inner diameter of pipe	0.014
2	Evaporator section	0.65
3	Condenser section	0.2
4	Total length	1.8

Water and ammonia are taken as two working fluids for comparative analysis. The area of initial fluid is taken to be of the same percentage as volume occupied by the working fluid (100 mL) in the heat pipe. The assumptions and dimensions are taken as per Hlaing et al [9]. The saturation temperature was set at 45 degrees considering the practical usability of the fluids, wherein water has a high boiling point and ammonia has a very low value of the same. Operating pressure for each case was calculated from the standard relations using the temperature. The analysis is carried out in ANSYS FLUENT with boundary conditions specified as follows in Table (2).

Table 2. Boundary conditions

S. No	Selection	Boundary Type
1	Evaporator section	Positive heat flux input
2	Empty column	Adiabatic
3	Condenser section	Convective heat rejection
4	Ends	Adiabatic

Water at NTP is used as the heat absorber at condenser section. The convection is taken to be natural. The geometry is meshed and discretized into 25694 nodes and 23946 elements. Mixture model on multiphase analysis is adopted to accommodate the evaporation-condensation mechanism that exists within the heat pipe with liquid as primary phase and vapor as secondary phase. The droplet size at secondary phase is set at default of 10E-5 m. Mass transfer is predominantly set from liquid phase to vapor phase within the system. An iso-surface at the middle section across the length of pipe is created for observation of variations in parameters of interest. Ideal cases of heat transfer are assumed.

The convective nature of the fluid is studied with help of the following dimensionless numbers:

1) Grashof Number: Gr = $g\beta\Delta T d^3/\nu^2$
2) Weber Number: We = $\rho v^2 l/\sigma$

3. Results and discussions

The aim of this analysis is the study of differences in heat transfer between two working fluids, which is defined with temperature distribution plot as follows.

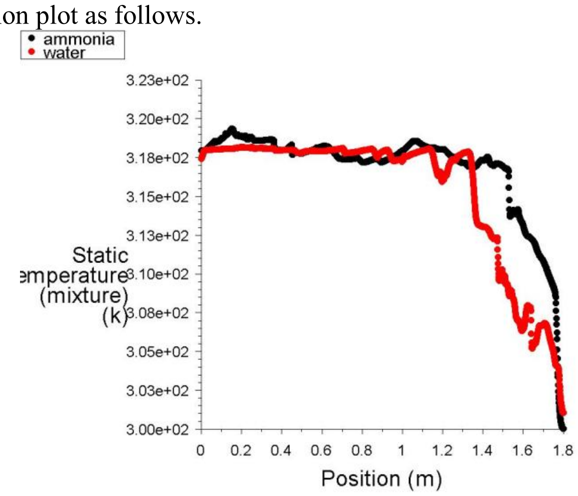

Figure 1. Comparative plot for temperature at section

The evaporator section for both cases is observed to start with similar temperature, which is well within the consideration of operational parameters. Throughout the empty column, a temperature drop is observed which is the effect of mass transfer and heat transfer between phases and flow of the working fluid. Water, in this case, is seen to have a relatively steeper decline in temperature as compared to ammonia, which denotes lesser retention of heat. This trend continues until the condenser wherein the heat recovered from each case by cool water has a pronounced variation. A substantial difference is seen between the temperatures of water and ammonia at the entrance to condenser region (approximately 8K) which further follows down to heat rejection. This plot is further substantiated by the individual temperature contours recorded as follows in Figure (2a) and (2b).

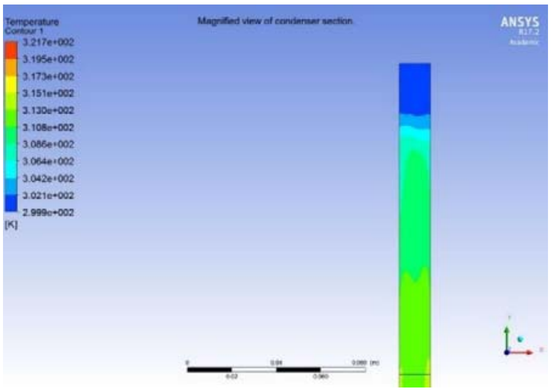

Figure 2a. Temp. profile of ammonia heat pipe.

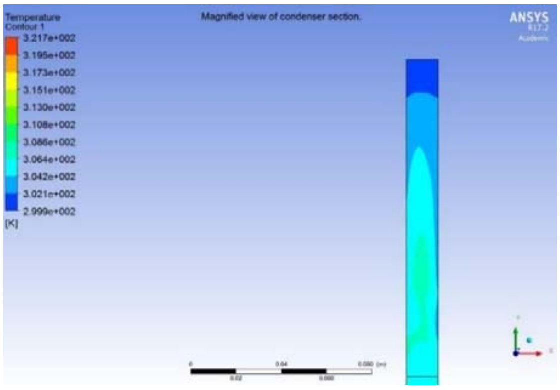

Figure 2b. Temp. profile of water heat pipe.

The inference that ammonia as working fluid allows more heat to be extracted from the same level of insolation is thus concluded.

Volume fraction (indicative ratio of constitution of each phase within a multiphase system) is a necessary parameter to understand the nature of flows in this system which is captured in Figure 3

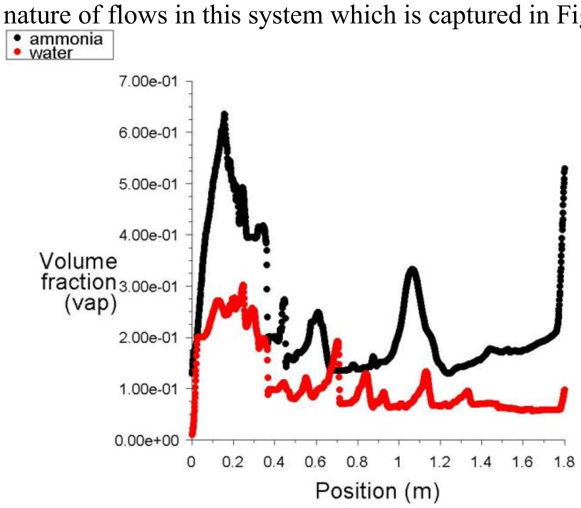

Figure 3. Comparative plot for vapor volume fraction at section.

The presence of vapor phase is seen to be highest in evaporator section, which follows from heat input. Throughout the evaporator section and even beyond, the vapor fraction is seen to vary without any common trend. Phase transitions by mass heat exchange at various points is deduced as the reason for such observation. The multiphase model taken is implicative of two phases in continuous interaction and further substantiates the irregularity in trend. The volume fraction of vapor available at condenser section is a measure of the available energy to be extracted from phase changes. Ammonia is observed to have a higher conversion fraction from liquid to vapor at the evaporator section, which is indicative of more heat absorption. This also is inferred from the lower latent heat of vaporization of ammonia as compared to water. The liquid volume fraction shows the converse of points discussed above and indicates water as working fluid to have proclivity towards liquid phase.

Figures 4a and 4b show the variation in Grashof number (taken for mixed phase) for respective working fluids, which is a measure of the extent of natural convection within the system.

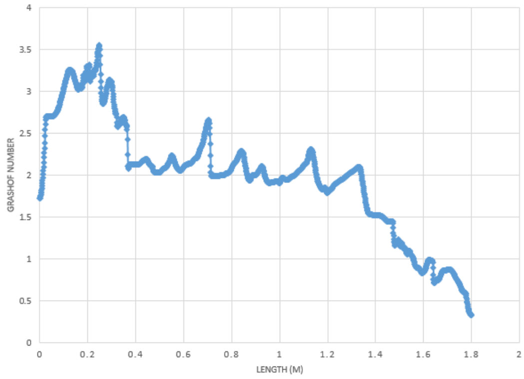

Figure 4a. Grashof number variation at section for water heat pipe.

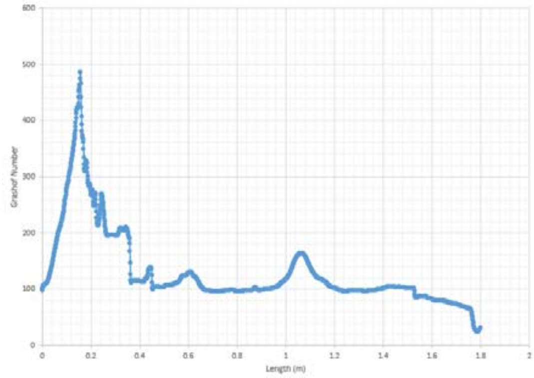

Figure 4b. Grashof number variation at section for ammonia heat pipe.

In both fluids, the number is highest at evaporator section following the boiling effect and reduces gradually towards the condenser section due to reversal of phase. Ammonia heat pipe is seen to have an extremely high convective tendency than that of water heat pipe. This is indicative of the proven fact of ammonia being a better agent for heat transfer than water.

The entrainment limit is a possibility further studied using Weber number across the section, which resulted in the Figure 5

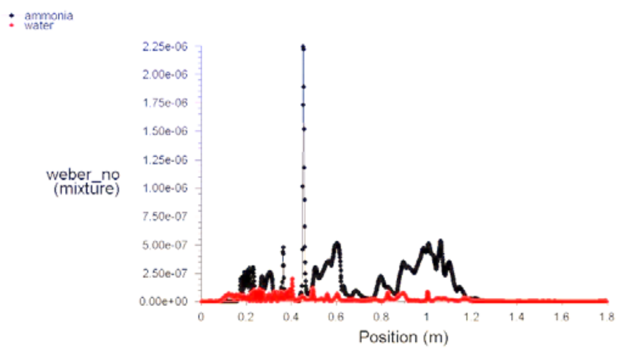

Figure 5. Weber number variation at section, combined graph.

The Weber number as the ratio of inertial force to viscous force of a fluid is observed to be lesser than unity for both fluids, which indicates the stronger influence of viscous flow of the droplets in secondary phase. This further leads to understanding that the entrainment of liquid coming down is eliminated. It also eludes the phenomenon of evaporation.

4. Conclusions

From the above discussion it is found that ammonia is observed to have higher heat transfer at condenser section than water. The difference in temperature between two cases is the extraction of 8 K of additional heat in the case of ammonia. Water is seen to have higher retention of liquid phase than ammonia. Conversely, ammonia is observed to vaporize at higher proportions at the same saturation temperature. Ammonia- based heat pipe ETC is proposed as an alternative to the existing flat plate collectors. Surface tension influences boiling-condensation phenomenon more than inertial and body forces.

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