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Analysis of the thermal cooling capacity of heat pipes under a low Reynolds number flow

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HIGHLIGHTS

- Thermal cooling capacity of water, ethanol and R134a established.
- CFD multiphase simulations validated against wind tunnel testing.
- Maximum heat transfer of 977 W achieved using water as working fluid.
- Water indicated airside temperature reduction of 24% higher than R134a.
- Error variation between CFD and experimental findings calculated at 3%.

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ABSTRACT

A detailed investigation into determining the optimum working fluid for providing passive airside cooling in ventilation airstreams was carried out. The effectiveness of water, ethanol and R134a as heat pipe fluids was systematically compared by analysing their thermal cooling capacity under a low Reynolds number airstream, typically found under natural ventilation. The internal multiphase flow profiles and the subsequent external air temperatures were numerically predicted using Computational Fluid Dynamics (CFD), the findings of which were quantitatively validated using wind tunnel experimentation. Using a source temperature of 314 K or 41 °C and an inlet velocity of 2.3 m/s, the emergent thermal profiles were established to comprehend the optimum working fluid. The results showed that the highest heat transfer due to convection was obtained using water as the working fluid, determined at 977 W. The corresponding effectiveness of the heat pipe heat exchanger was found to be 6.5% for water, 4.9% for R134a and 3.7% for ethanol. The findings determined that water incorporated the greatest capability of efficiently reducing air temperatures by approximately 24% higher than the refrigerant R134a and 42% higher than ethanol which was found to be the least effective working fluid under the range of investigated temperatures. Good correlation was obtained between the numerical and experimental findings with a maximum error variation of approximately 3%. The present work successfully classified the sustainable operation of replacing synthetic refrigerants with a natural fluid such as water in delivering energy-free cooling under ventilation airstreams.

1. Introduction

Requirements for comfortable working conditions have resulted in an increased demand for air conditioning, likely achieved through mechanical cooling systems consuming electricity as the principal source of energy. Refrigerant based thermodynamic cycles have been the preferred choice for heating, ventilation and air-conditioning (HVAC) for more than four decades despite their high global warming potential [1,2]. This method of operation takes advantage of the way phase transition work, wherein latent heat is released at a constant temperature during a liquid/gas phase change, and where varying the pressure of a pure substance also varies its condensation and boiling points. However, the potential of replacing a synthetic refrigerant with a natural working fluid such as water is vast and can lead to a significant reduction in the carbon footprint of the residential dwelling if implemented correctly. When considering low-energy cooling for a built environment, the choice of working fluid becomes even more significant in order to ensure that the indoor air quality remains free at all times from any pollutants within the occupied space [3].

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Nomenclature

A	cross sectional area (m^2)
ρ	density of liquid (kg/m^3)
ε	effectiveness of heat exchanger
g	gravitational acceleration (m/s^2)
q_{actual}	heat transfer, actual (W)
q_{max}	heat transfer, ideal (W)
q_e	heat transfer rate to evaporator (W)
h_{fg}	specific enthalpy (J/kg)
c_p	specific heat capacity of liquid (J/kg K)
ΔT	temperature difference (K)
$T_{c,inlet}$	temperature at inlet to condenser (K)
$T_{e,inlet}$	temperature at inlet to evaporator (K)
$T_{e,outlet}$	temperature at outlet from evaporator (K)
U	velocity (m/s)

One method for alleviating mechanical cooling loads of a built environment can thus be achieved by integrating natural ventilation systems with a heat pipe heat exchanger technology. By incorporating the zero-energy working principles of heat pipes to provide the cooling duty, natural ventilation systems can become an effective and sustainable alternative in keeping the internal environment comfortable. A heat pipe is a heat and mass transfer mechanism used in many applications for transferring thermal energy from one airstream to another without the need for mechanical intervention. A heat pipe unit typically uses a refrigerant (synthetic or natural) to carry out its heat transfer mechanism; therefore there are extensive opportunities in order to compare the working performance of these refrigerants appropriate to both building physics and ventilation sectors [4–6].

Research on emphasising the capability of heat pipes in pre-cooling warm fresh air streams to advance natural ventilation systems for buildings or residential dwellings are limited. Previous works have highlighted the use of heat pipe devices in building heat recovery and energy conservation systems although the potential for passive cooling is not well-defined, specifically in terms of the choice of working fluid. This work therefore investigated the convective heat transfer and effectiveness of ideal heat pipe working fluids for providing passive cooling when operating under ventilation airstreams carrying high ambient temperatures.

2. Previous related work

Previous studies obtained from literature have highlighted the use of natural and synthetic refrigerants as heat pipe working fluids in a broad range of applications within the range of intermediate working temperatures, appropriate to areas of hot natural climates.

Abou-Zian et al. [7], designed and constructed a two-phased closed thermosiphon in order to predict its thermal conductivity performance characteristics under stationary and vibrated conditions. Water and R134a were used as working fluids. The copper pipe had an internal and outer diameter of 23 mm and 25 mm while measuring 900 mm in total length. The evaporator section was heated through an electric heater having a power of 1500 W. The condenser section was cooled using flowing water through an annular jacket measuring 250 mm in length. The vibration frequencies were in the range between 0 and 4.33 Hz. The results of the work depicted a maximum heat transport of stationary water-copper thermosiphon at 1100 kW/m^2 while the R134a charged thermosiphon displayed 190 kW/m^2. It was found out that the effect of vibration on the wickless pipes was different for both fluids due to their different thermophysical properties.

De Leeuw et al. [8], carried out work on comparing the performance of a heat pipe heat exchanger to a conventional water-cooled heat exchanger. R134a was used as the working fluid and the study analysed the overall heat transfer under inlet mass flow rates varying from 0.4 kg/s to 2 kg/s. The temperature of the hot channel was kept between 40 and 70 °C while ambient air was used as the cold sink keeping temperatures regulated between 20 and 50 °C. A mathematical model was developed in order to predict the heat transfer performance and a good correlation was observed when the results were compared against published pool boiling and filmwise condensation models at low Reynolds number. The overall heat transfer at the evaporator side was measured between 10 and 40 W/m^2K with the temperature distribution being indicative of proper fluid filling ratio. The study emphasised that the testing conditions were kept similar to countries experiencing warmer climates with the constant possibility in applying heat pipe based cooling technology in practice.

Wong et al. [9] analysed the evaporator resistance performance of heat pipes charged with water, methanol and acetone as working fluids. A sintered two layer copper wick was used and uniform heating was applied to the copper base plate at the evaporator section. The condenser section was kept at constant cold temperature using a water jacket at 20 °C. The evaporator resistance was determined using the temperature difference between the copper plate and the vapour under and above the evaporator section. The findings of the work revealed that maximum heat loads for water were superior to methanol and acetone. The work concluded that the values for heating loads correlated well with their figure of merit highlighting the superiority of water over the compared fluids.

Chaudhry et al. [3] compared different heat pipe working fluids in terms of their Merit No. for particular use in building and ventilation systems. Water, ammonia, acetone, pentane and heptane were equated based on their thermophysical fluid properties and the review study revealed that water incorporated the highest Merit No. in relation to other working fluids. At an operating temperature of 293 K, the Merit No. for water was 1.78×10^{11}, which was an order higher than ammonia which incorporated a Merit No. of 7.02×10^{10}. In addition, with an increasing operating temperature gradient from 293 K to 393 K, water displayed an increase in Merit No. of 64% while other working fluids displayed a reduction in Merit No. as the operating temperatures were increased. The study identified the scope of further research into comparison between available heat pipe working fluids in order to evaluate the ideal candidate for use under the working temperatures suitable for natural ventilation.

This study investigates the cooling capacity associated with water, ethanol and R134a as heat pipe working fluids when subjected to low-speed external airflows carrying ambient temperatures varying between 295 K and 314 K typically found in regions with hot and dry climates such as Qatar [10]. Keeping the geometrical arrangement and external boundary conditions fixed, the multiphase flow profile inside the heat pipe and its subsequent effect on the incoming airstream was investigated. The rate of heat transfer and effectiveness of the system was determined using both CFD and experimental techniques and a correlation between the results was obtained. This work classified the ideal working fluid associated with passive cooling by achieving a detailed comparison between three of the most commonly used heat pipe working fluids.

3. Computational domain

The computational domain comprised of the purpose-built heat pipe geometry, which was constructed in order to carry out the