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Thermal Performance of a Two-Phase Closed Thermosyphon for Waste Heat Recovery System

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Abstract: Performance study of a two phase closed thermosyphon was experimentally investigated. The experiments were carried out for different filling ratios of 30 to 90% with input heat transfer rates of 0 to 1000 W and for various working fluids such as distilled water, ethanol, methanol and acetone. Investigations were focused to find the influence of the filling ratio, maximum heat transport capability for various working fluids in a vertical two phase closed thermosyphon. The maximum heat transport capability was found to be high for water compared to other fluids such as ethanol, methanol and acetone, at the operating temperatures higher than 40°C.

Key words: Thermosyphon, heat transport capability, filling ratio, waste heat recovery, heat transfer characteristics, thermal performance

INTRODUCTION

The two phase closed thermosyphon is a simple but effective heat transfer device. It is a vertically oriented wickless heat pipe with a pool at the bottom. The thermosyphon is described by dividing it into three sections (Japikse, 1973) as shown in Fig. 1. Heat is supplied at the bottom evaporator section, where the liquid pool exists and it is utilized to convert the working fluid into a vapor. The vapor rises and passes through the adiabatic section to the top condenser section. In the condenser section, the vapour condenses and gives up its latent heat. The gravity effect returns the condensate back to the evaporator.

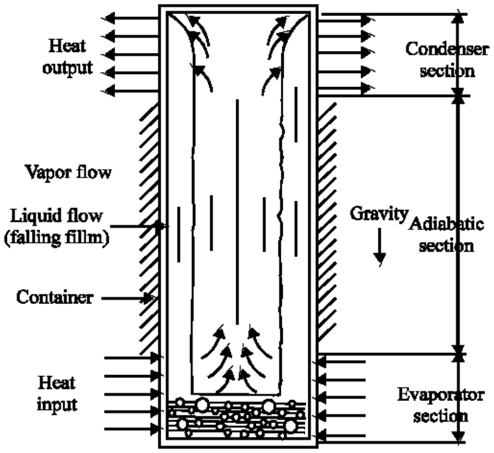

Fig. 1: Schematic of closed two phase thermosyphon

Due to high efficiency, reliability and cost effectiveness, the thermosyphons are being used in many applications. Some of the common applications of heat pipe include turbine blade cooling, waste heat recovery, heat exchanger fins, electrical motor cooling, transformer cooling, nuclear reactor cooling, cryogenic cool down apparatus, cooling of internal combustion engines etc., (Faghri, 1995).

For the past many years a considerable experimental and theoretical work have been carried out on the application and design modification for improving thermosyphon performance. Khandekar *et al.* (2008) analyzed thermal performance of closed two phase thermosyphon using various water based nanofluids as the working fluids. Jiao *et al.* (2008) has developed a comprehensive steady state model considering five forms to investigate the effect of filling ratio on the heat transfer performance of a vertical two phase closed thermosyphon. Chang *et al.* (2008) used a vapor chamber as an evaporator and studied three factors that influence the thermal performance of the cooling system. Noie (2005) considered the aspect ratio and filling ratio on the thermal performance of the thermosyphon with

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water as the working fluid. Vasiliev (2004) analyzed different types of heat pipe design for electronic cooling. Haider and Joshi (2002) proposed an analytical approach to model a closed two phase thermosyphon. Park *et al.* (2002) studied the heat transfer characteristics of a two phase closed thermosyphon using FC-72 (C_6 F_{14}) as the working fluid.

Cao and Gao (2002) employed the concept of boiling heat transfer mechanism in a narrow space in the two flat plate wickless network heat pipes with water and methanol as the working fluids. Payakaruka *et al.* (2000) investigated the effects of bond numbers, froude numbers, weber numbers and kutateladze numbers on the heat transfer rate and total thermal resistance. EI-Genk and Saber (1999) developed the correlation to calculate the expanded pool height in the evaporator for the acetone, ethanol and water in the closed two phase thermosyphons.

Dobson (1998) observed the two phase flow in a metal thermosyphon by using air and water in a Perspex tube. Nakano *et al.* (1998) studied the heat transfer characteristics, the thermal resistance and maximum heat transfer rate of a nitrogen thermosyphon over a large dynamic range from near the triple point to the critical point. Lin and Faghri (1997) analyzed a one dimensional mathematical model for natural circulation two phase flow in a thermosyphon with the tube separator.

Monde (1996) studied the critical heat flux of a two phase thermosyphon. Zuo and Gunnerson (1994) studied the effects of operating temperatures, geometry, working fluid inventory and condenser thermal capacity of two phase closed thermosyphon. Lock and Fu (1993) investigated the performance of an offset, evaporative thermosyphon aligned vertically. Li *et al.* (1991) studied the performance of closed thermosyphons charged with fluids R11, R22 and water operating at low temperature differences between evaporator and condenser section. Bontemps *et al.* (1989) tested the large dimension, inclined closed two phase thermosyphon for the temperature range of 100 to 300°C with toluene as the working fluid. Hahne and Gross (1981) investigated the effect of inclination angle on the closed two phase thermosyphon. Imura *et al.* (1977) studied the heat transfer characteristics in a closed-type thermosyphon with water and ethanol as working liquids.

The new equipments being used in the emerging area of recent technologies demand for the better heat pipes for the efficient transfer or dissipation of heat. This experimental study focuses on the behavior of thermosyphon (wickless heat pipe) to understand the maximum heat transport capability of different working fluids.

The present study analysis the thermal performance of two phase thermosyphon for various working fluids with different filling ratios and operating temperatures and determines the maximum heat transport capability.

MATERIALS AND METHODS

The thermosyphnon was designed and fabricated in 2006 and a series of experiments were conducted during 2007-2009, with water, ethanol, methanol and acetone as working fluids.

The experimental setup are shown in Fig. 2, was used for studying the thermal performance of a two phase closed thermosyphon for different operating temperatures and for various working fluids. The test rig consists of a heater, a liquid reservoir for charging, a thermosyphon (wickless heat pipe), a cooling section and also measuring instruments. The upper part of the thermosyphon was equipped with a seal valve for connection to a mechanical vacuum pump and to the working fluid charging line. A mechanical vacuum pump capable of creating vacuum up to 0.5 Pa used for partial elimination of the Non Condensable Gases (NCG) from the thermosyphon. Complete extraction of NCG was achieved by purging.

The details of thermosyphon with an electric heater for evaporator section and a water jacket for condenser section are shown in Fig. 3.

The thermosyphon consist of 1000 mm long tube having an inside diameter of 9.5 mm and outside diameter of 12.5 mm. The tube was sealed at one end and was provided with a vacuum valve at the other end. The evaporator section has the length of 300 mm and adiabatic section has the length of 200 mm. The condenser section of the pipe consisted of a 500 mm long (40 mm OD) concentric tube acting as a cooling water jacket surrounding the pipe.

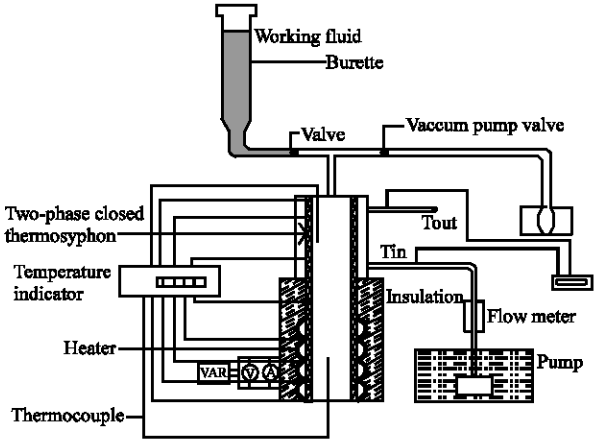

Fig. 2: Schematic of the test rig

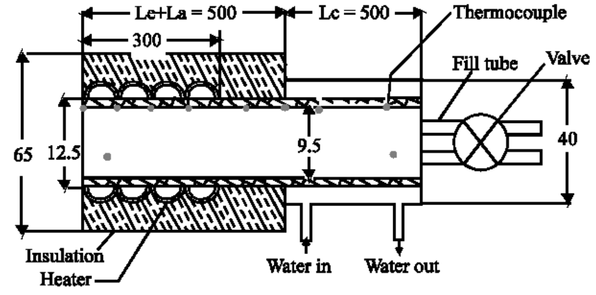

Fig. 3: Details of thermosyphon

An electrical resistance of a nominal power range of 0 to 1000 W was wrapped around the evaporator section, which is used to heat the evaporator. To prevent the heat loss to the atmosphere, the electrical elements were insulated by glass wool having a thickness of 65 mm. The heat was removed from the condenser section by the water jacket as described above in the introduction.

The power supplied to the evaporator section was determined by monitoring the applied voltage and current with accuracy of ±2%. The accuracy of flow measurement was estimated to be around ±2%. A variable voltage controlled the rate of heat transfer the evaporator. Temperature distribution along the thermosyphon was measured using Ni-Cr thermocouple.

Thermocouples were mechanically attached to the surface of the pipe. The vapour temperature was measured by thermocouple T_9 and T_{10} attached to the top and bottom surface of thermosyphon as shown in Fig. 4. The upper surface of thermocouple was fully insulated and the vacuum pressure also measured by using the vacuum pressure gauge. The experiments were conducted for 4 different working fluids. Temperatures were simultaneously acquired from 8 locations in the wall of the thermosyphon, four at evaporator section, one in the adiabatic section and three in condenser section over the entire length of the thermosyphon as shown in Fig.4.

In order to find out the effects of maximum heat transfer capability on the thermal performance of the thermosyphon a series of test were carried out for the following conditions:

Input heat transfer rate range : 0 to 1000 W
Filling ratio (%) : 30, 40, 50, 60, 70, 80, 90
Operating temperature (°C) : 30, 40, 50, 60, 70
Working fluids : Distilled water, ethanol, methanol, acetone

Test procedure began by charging a required working fluid. In the first series of experiments, the thermosyphon was filled with distilled water. The thermal performance of the thermosyphon for different working filling ratio and operating temperature was investigated.

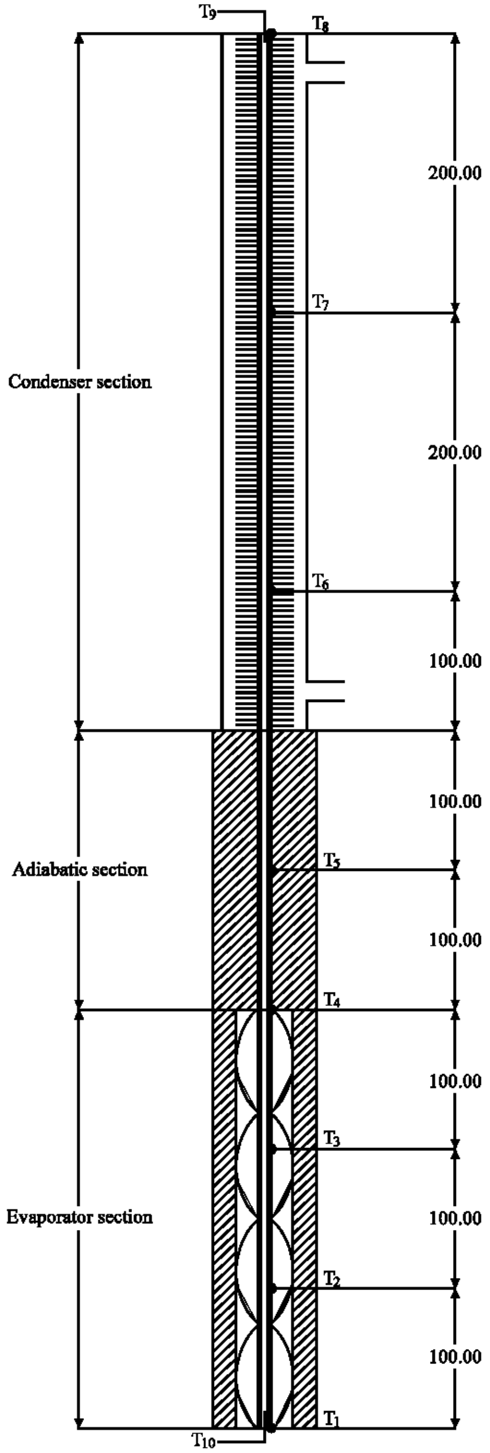

Fig. 4: Location of thermocouples

Maximum heat transport capability was measured by subjecting the thermosyphon to cyclic variation of heat input. The power input was increased linearly from 0 W to nominal power. The maximum power, at which the wall temperature of thermosyphon was high, was recorded. At that condition the maximum heat transport rate was measured. This procedure was repeated for all working fluids.

Performance of closed two phase thermosyphon: Three different types of performance limitations are observed in the investigation of closed two phase thermosyphon.

- The dry out limitation is observed in low filling ratio. In this case, the returning condensate flow is reduced before reaching the evaporator. Then the level of liquid pool is slowly lowered and finally the evaporator wall gets dried out completely
- The boiling limit or burn out limitation is noticed in high liquid filling ratio and high radial heat flux in the evaporator section
- The entrainment or the flooding limitation is encountered for high axial heat flow at small radial evaporator heat flux

The following correlation between the maximum heat transport capability and the various influence parameters was used (Groll and Rosler, 1992) to verify the measured results.

$$Q_{max} = \{f_1 f_2 f_3 L(\rho_v)^{1/2}[\gamma g(\rho_l - \rho_v)]^{1/4}\}A'_E \qquad (1)$$

RESULTS AND DISCUSSION

The maximum heat transport capability with respect to the operating temperature for different working fluids (water, methanol, ethanol and acetone) at various filling ratios were calculated and the results have been plotted in Fig. 5-9.

Figure 5 shows the maximum heat transport capability variation for different working fluids, at 30°C. It was high for methanol for all filling ratios, compared to other working fluids, at the operating temperature 30°C. A maximum heat transport of about 300 W was observed for methanol at 55% filling ratio. The change in filling ratio seems to have a marginal change in the heat transport rate and it is less than 3%. Figure 6 shows the maximum heat transport capability variation at 40°C and it is observed to be high for water, although the variation with the filling ratio exhibited the same trend. Similarly, Fig. 7-9 show the maximum heat transport capability variation at 50, 60 and 70°C, respectively. For all temperatures in the range of 40 to 70°C, water is found to have comparatively high heat transport capability at all filling ratios. Maximum heat transport capability for acetone is relatively low at all operating temperatures for all filling ratios. In the temperature range of 40 to 70°C, the heat transport capability of methanol is found to be higher than acetone but less than methanol.

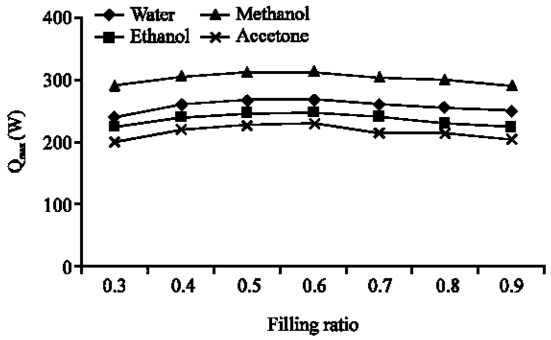

Fig. 5: Maximum heat transport capability vs. filing ratio of thermosyphon for operating temperature 30°C

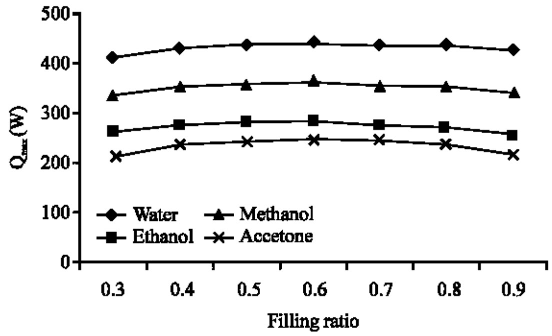

Fig. 6: Maximum heat transport capability vs. filing ratio of thermosyphon for operating temperature 40°C

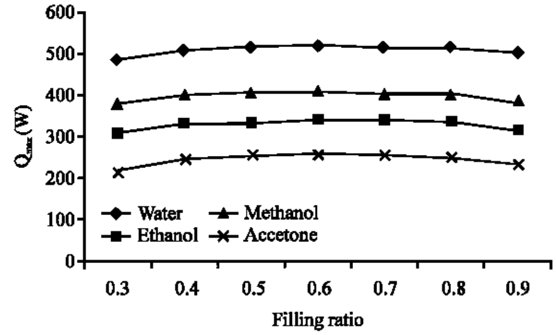

Fig. 7: Maximum heat transport capability vs. filing ratio of thermosyphon for operating temperature 50°C

As the operating temperature is increased from 40 to 70°C, the maximum heat transport capability is also increased from 425 to 650W for water. As the operating temperature is increased, the improvement in the heat

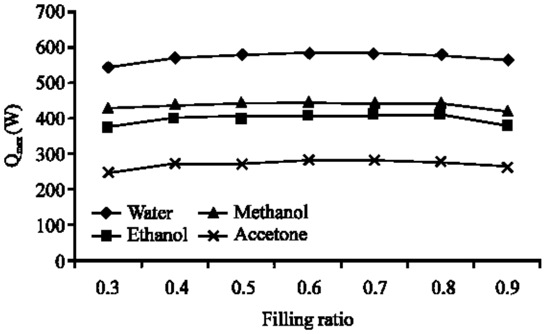

Fig. 8: Maximum heat transport capability vs. filing ratio of thermosyphon for operating temperature 60°C

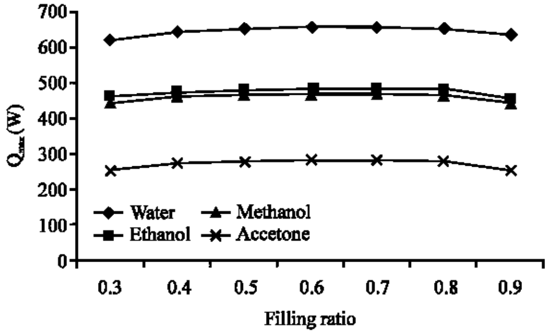

Fig. 9: Maximum heat transport capability vs. filing ratio of thermosyphon for operating temperature 70°C

transport capability of acetone is found to be marginal. At higher temperature (say 70°C), the difference in the performance of the methanol and ethanol is found to be narrow.

Comparison between the predicted maximum heat transport rate according to Eq. 1 and experimental results were carried out for about 100 experimental data points. The agreement between prediction and experimental result was found to be good and the discrepancy was less than ±14%.

Groll *et al.* (1980) has studied the maximum heat transport capability at various tilting angles, with water as working fluid and also studied the influence of surface roughness on maximum heat transport capability. The results of this study fairly matches with the trend observed by Groll *et al.* (1980).

CONCLUSIONS

The effect of the different working fluids with various filling ratios on the maximum heat transport rate of a closed two-phase thermosyphon under normal operating conditions were investigated in this work in the range of heat input of 0 to 1000 W. The following results were obtained.

- The maximum heat transport capability showed a increasing trend with increasing operating temperature. The effect of filling ratio on heat transport capability was only marginal for all fluids
- The heat transport limitations were observed in different ways with various filling ratios. For a small filling ratio (FR<20%) it occurred by the dryout limitation. While for the large filling ratio it occurred by the flooding limitation
- Maximum heat transport capability was observed for water at all operating temperatures higher than 40°C. However, the methanol was found to have better heat transport capability if the operating temperature was less than 30°C
- Maximum heat transport capability was found to strongly depend on the operating temperature. As the operating temperature is increased from 40 to 70°C, the maximum heat transport capability is also increased from 425 to 650W for water

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NOMENCLATURES

A'_E = Cross sectional Area of evaporator (m^2)
B_O = Bond No. = $d_i\,(g\,(\rho_l\text{-}\rho_v)/\gamma)^{0.5}$
d_i = Inner diameter of pipe (m)
d_E = Diameter of evaporator (m)
f_1 = Constant expressed as a function of the Bond Number (B_O)
f_2 = $k_p^{-0.17}$ if $k_p < 4\times10^4$
f_2 = 0.615 if $k_p > 4\times10^4$
f_3 = 1 for inclination angle of 90°
FR = Filling ratio (ratio of volume of working fluid to volume of evaporator) of the working fluid at room temperature
g = Gravitational acceleration (m sec^{-2})
k = Thermal conductivity (W m^{-1} °C)
k_p = Dimensionless pressure parameter = $p_v/((\rho_l\text{-}\rho_v)\,g\gamma)^{0.5}$
L = Latent heat of vaporization (J kg^{-1})
p = Pressure (Pa)
q = Heat flux (W m^{-2})
Q_{max} = Maximum Heat transport capability (W)
T = Temperature (°C)

Greek symbols

ρ = Density (kg m^{-3})
γ = Surface tension (N m^{-3})

Subscripts

l = Liquid
o = Outer, outlet
v = Vapour

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