The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

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Abstract

When traditional air-to-air cooling is too voluminous, long thermosyphons may offer a way out. For safe operation of heat exchangers equipped with thermosyphons, the limiting heat flux \( q''_{\text{lim}} \) is an important design parameter.

Some literature is found to deal with the operation limiting heat flux of closed two-phase thermosyphons. However, R-134a filled thermosyphons with large length-to-diameter (188) are hardly investigated up to now. Extrapolation of existing correlations to predict \( q''_{\text{lim}} \) in this case results in large scatter. The effect of the angle of inclination on \( q''_{\text{lim}} \) has not been considered until now.

Dedicated experiments with a single thermosyphon with a large length-to-diameter ratio (188) and filled with R-134a are presented and analyzed. Effects of saturation temperature, filling ratio and angle of inclination, \( \beta \), on the operational limiting heat flux have been investigated. The thermosyphon functions properly if \( \beta < 83^\circ \) and \( q''_{\text{lim}} \) is found to increase with increasing \( \beta \). With decreasing saturation temperature, \( q''_{\text{lim}} \) increases. The filling ratio is found not to be crucial if it exceeds 25 %.

Correlations are presented to accurately predict the operation limiting heat flux for thermosyphons with a \( L/d \) ratio up to 188. Because of the accounting for the above new aspects, these correlations are also relevant for filling refrigerants other than R-134a.

Keywords: heat pipe, thermosyphon, heat exchanger, R-134a, limiting heat flux
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1. Introduction

Stand-alone electricity power generators are usually cooled with ambient air. In warmer countries, heat pipe equipped heat exchangers provide an alternative for air-to-air heat exchangers at low air temperature differences. In this case, two plate heat exchangers are coupled with multiple wickless heat pipes, so called thermosyphons [1]. Advantages of heat pipes are high heat recovery effectiveness, compactness, no moving parts, light weight, relative economy, no external power requirements, pressure tightness, no cross-contamination between streams and reliability [2, 3]. Vasiliev [4, 5] gives an overview of applications of heat pipes and thermosyphons.

Safe operation of thermosyphons is principally dependent on knowledge of the limiting heat flux. A number of researchers have investigated this maximum heat flux [6-21]. However, a large scatter in results was found. This scatter has several causes: a large variety of working fluids, temperature and pressure ranges, diameters, evaporator length, filling ratios and the nature of the limit; boiling critical heat flux, entrainment limit, flooding limit etc.

Research on the effect of the angle of inclination on thermosyphon characteristics is often contradictory [9, 16, 21 and 22]. The changes in fluid flow possibly affect the operation limiting heat flux, although no general conclusions on the effects of angle of inclination on the operation limiting heat flux can be drawn from literature. Research on thermosyphons found in literature deals with much shorter thermosyphons than the one considered in the present research. We selected a high L/d ratio in order to highlight and elucidate the effect of the angle of inclination on the limiting heat flux.

The operational heat flux limit of long, R-134a filled thermosyon has hardly been investigated up to now. Existing correlations to predict the limiting heat flux in thermosyphons result in large scatter if extrapolated to our specific geometry and working fluid. This will be shown in section 4. As stated above, the effect of inclination on the limiting heat flux is not clearly predicted. To promote commercial use of heat pipe equipped heat exchangers, the limiting heat flux of a single 3 m thermosyphon with a large length-to-diameter ratio of 187.5 should be determined in a wide operating range.

For the above reasons, this study presents measurements and predictions on the operation limiting heat flux of a thermosyphon with a length of 3 m and a large length-to-diameter ratio of 187.5. The
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thermosyphon is filled with R-134a as working fluid, to prevent freezing [1]. The goal of this research is to determine the effect of the angle of inclination on the operation limiting heat flux of the thermosyphon. Relationships between filling ratio, inclination angle and operation limiting heat flux will be derived, in order to facilitate future design of heat exchangers equipped with thermosyphons / heat pipes of this type. These main results can be seen as an addition to the many applicability maps existing, see for example the ESDU Data Item [23]. Conclusions for evaporation and condensation heat transfer in this type of thermosyphon have been presented in a previous paper [24].

2. Experimental

The experimental setup is described in detail in [24]. A schematic overview is shown in Fig. 1. The main features are summarized in table 1. Note that the length to diameter ratio of the thermosyphon is large: 187.5. Experiments are performed with a filling ratio of 25%, 62% and 100%. The filling ratio is defined as Eq. (1):

\[ F_r = \frac{V_f}{V_{evap}} \]

(1)

Where the evaporator volume, \( V_{evap} \) is \( \pi r_i^2 L_{evap} \) with \( r_i \) is 7.2 mm and the volume of fluid, \( V_f \), is the volume of liquid plus the volume that would be obtained if the vapour is condensed to liquid. Measurements are performed at inclination angles \( \beta \) from 0° to 87°. The angle is determined with a Mitutoyo Pro 360 Digital Protractor which is accurate to 0.2°. The saturation temperature inside the thermosyphon is varied between 20°C and 75°C. This corresponds with pressures of 5.7 – 20.6 bar. The uncertainties of all measured and calculated parameters are estimated according to [25].

3. Experimental results

The following results will be presented:

- Typical temperature distributions over the thermosyphon at the operation limiting heat flux.
- Operation limiting heat flux dependencies on saturation temperature and filling ratio.
- Operation limiting heat flux dependencies on the angle of inclination.
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Figure 2 shows a typical example of measured wall temperatures at the operation limiting heat flux, for a filling ratio of 62%. At inclination angles exceeding 83° and saturation temperature of 75°C, the operation limiting heat flux is observed to occur differently, see Fig. 3. All wall temperatures at the evaporator stabilize at a temperature level far above \( T_{\text{sat}} \), starting with the evaporator end followed by places further away in the direction of the condenser section. The temperature at the bottom end of the evaporator is found to fluctuate, as if dry-out occurs intermittently.

As shown in Fig. 4, the operation limiting heat flux at vertical orientation at various filling ratios is observed to decrease with increasing saturation temperature. The trend of a decreasing operation limiting heat flux with increasing temperature is coherent for all measurements, also when the thermosyphon is inclined. At a saturation temperature of 20°C the operation limiting heat flux, based on the evaporator wall area, is 17 kW/m², corresponding to a heat flow rate of 900 W. The operation limiting heat flux decreases to 9.2 kW/m² around 80°C. Only one point at 25% filling ratio is measured. At higher temperatures, only the gaseous phase is present at this underfilled case. The effect of filling ratio is found to be negligible as long as the fluid inventory is sufficient to avoid dry out at normal operation.

A higher operation limiting heat flux is observed at a higher angle of inclination at a saturation temperature of 20°C in Fig. 5: from 17 kW/m² in vertical orientation to 22 kW/m² in almost horizontal position. The trend of an increasing operation limiting heat flux with increasing inclination is also observed at a saturation temperature of 75°C. The error bars in Fig’s 4 and 5 account for the reproducibility of the measurements at the operation limiting heat flux.

4. Analysis

4.1. Interpretation of operation limiting heat flux

Figure 2 shows an entrainment limit: the temperature at the evaporator bottom end increases due to a lack of liquid. The liquid does not reach the end of the evaporator because it evaporates before that time and because vapour shear forces probably entrain remaining liquid. The occurrence of an entrainment limit at filling ratios of 62% and 100% is in agreement with findings of Golobic et al. [6] and Abou-Ziyan et al.
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[7]. Park et al. [8], observed a boiling limit at filling ratios of 50% and higher. Park et al. did observe entrainment limits, but only at a low filling ratio of 10%.

Shiraishi et al. [26, 27] visualized the flow behaviour at almost horizontal position with a 13 mm diameter glass tube filled with R-113. The observed flow patterns agree with the measured temperature histories of our measurements in Fig. 3. In almost horizontal position, liquid can easily flood the condenser. Flooding causes a breakdown of the condensation process and dry patches in the evaporator section due to an increase of void fraction in the evaporation section. Breakdown of the condensation process due to flooding is in agreement with the results of Gross [28]. From results found by Gross [28] and Shiraishi [26, 27], it is reasonable to conclude that the measured temperature fluctuations at the evaporator bottom end for angles of inclination larger than $83^\circ$ are due to the boiling limit.

4.2. Operation at inclination

Since fluid transport in a thermosyphon is gravity driven, functioning of the thermosyphon would be expected to degrade with increasing $\beta$. The contrary is observed: the limiting heat flux increases with increasing $\beta$. Proper functioning of the thermosyphon up to large angles of inclination is not surprising with regard to the wall wetting phenomena observed in Fig. 6. In these visualizations, we took care to have the same contact angle as in the present measurements. Drop impingements from droplets escaping the evaporator section prove that the wall is still fully wet at inclination. A droplet escapes from the evaporator section and hits the adiabatic wall of the thermosyphon. The droplet spreads out and induces waves, proving that a liquid surface and a liquid film are present. This proves that local dry-out of the wall does not occur at increasing angle of inclination. Visualizations of flow phenomena in thermosyphons have been presented in previous work [29].

4.3. Application of existing correlations to predict the limiting heat flux

Some correlations from the literature to predict the operation limiting heat flux are shown in Figure 7. Note that these correlations do not take the angle of inclination into account. The operation limiting heat flux predicted with correlations of Tien et al.[10] and Nejat [11], agrees to within 1.8 kW/m$^2$ with the present data, if these correlations are extrapolated to our geometry with $L/d = 187.5$, to our working fluid R-134a and taking vertical orientation into account only.
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4.4. New correlation to predict the limiting heat flux including angle of inclination and for \( L/d \) up to 188

Both correlations of Tien et al. and Nejat are in the form of

\[
q^* = a_1 \cdot f \left( Bo^{\frac{1}{2}} \right) \cdot \left( \frac{d}{L_{\text{evap}}} \right)^{a_2}
\]

with \( a_1 \) and \( a_2 \) constants and with \( Bo \) the Bond number, defined as \( \sqrt{\rho_f g d^2 / \sigma} \). \( L_{\text{evap}} \) is the length of the evaporator section, 1.20 m, \( d \) the diameter of the thermosyphon, 16 mm, and \( q^* \) the heat flux per evaporator wall area \( A_{\text{evap}} \). The form of these correlations appears to do well to predict the trends in the present data. Both geometrical properties and working fluid properties are incorporated. We have tried to fit the measured data in a correlation of this form. Fit parameters from Tien are \( a_1 = 0.8 \) and \( a_2 = 1 \), fit parameters from Nejat are \( a_1 = 0.09 \) and \( a_2 = 0.9 \). The following equations (6, 7) are found to be valid for a thermosyphon with R-134a at saturation temperatures between 20°C and the critical temperature (101°C):

\[
Ku = \left( 0.14 \pm 0.01 \right) \left( 1 - \frac{T_{\text{sat}}}{T_c} \right)^{\frac{1}{2}} Bo^{\frac{1}{2}} \left( \frac{d}{L_{\text{evap}}} \right)^{0.90 \pm 0.02} \left( \frac{\rho_v}{\rho_i} \right)^{\frac{1}{4}}
\]  

(6)

\[
q_{\text{lim,0}}^* = Ku \cdot \Delta h_{\text{fg}} \cdot \rho_v^{\frac{1}{2}} \left( \sigma g (\rho_i - \rho_v) \right)^{\frac{1}{4}}
\]

(7)

With \( T \) in K and \( T_c \), the critical temperature of R-134a, 374 K. The two errors in Eq. (6) indicate a 95% confidence interval. The heat flow rate on the evaporator side is for each heat flux given by

\[
Q_{\text{evap}} = q_{\text{lim,0}}^* \cdot A_{\text{evap}}, \text{ of course.}
\]

The term \( 1 - \frac{T_{\text{sat}}}{T_c} \) in Eq. (6) ensures agreement with the boundary condition \( q^* = 0 \) kW/m² at the critical temperature \( T_c \). The term \( \left( \frac{d}{L_{\text{evap}}} \right) \) accounts for geometrical properties of the thermosyphon, as in the correlation of Tien and Nejat. The thermodynamic and transport
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properties of the working fluid appear in Eq. (6) via the term \(1 + \left(\frac{\rho_f}{\rho_v}\right)^{\frac{1}{4}}\) and via

\[
\Delta h_f, \rho_v^{\frac{1}{2}}, \sigma, (\rho_i - \rho_v) \in \text{Eq. (7)}.
\]

The correlation coefficient \(r^2\) is defined by [30]:

\[
r^2 = \frac{\sum_{i=1}^{N} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2}
\]

where \(N\) is the number of measurements with outcome \(y_i, \hat{y}_i\) are the corresponding predictions with the fit function, and \(\bar{y}\) is the average of the set \(\{y_i\}\). The number of parameters used in the fit, \(k\), of course affects the quality of the fit. Whereas the correlation coefficient should preferably have a value close to 1, the parameter \(F\) should at the same time have a maximum value:

\[
F = \left\{ \frac{\sum_{i=1}^{N} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2} \right\} \cdot \frac{(N - k)}{(k - 1)}
\]

For Eq’s (6, 7), fit statistics of data measured at a filling ratio of 100\% are \(F = 29\) and \(r^2 = 0.94\). For data measured with a filling ratio of 62\%, fit statistics are found to be \(F = 130\) and \(r^2 = 0.97\).

Equations (6, 7) hold for a vertical orientation of the thermosyphon. However, from Fig. 5 we conclude that an increase of the inclination angle increases the operation limiting heat flux at all saturation temperatures. We propose to add this dependency of the operation limiting heat flux on inclination angle by using:

\[
d'_{\text{lim}} = q'_{\text{lim},0} \left(1 + \left(b_1 \frac{T_{\text{sat}}}{T_c} + b_2 \right) \cdot \beta \right)
\]

with \(q'_{\text{lim},0}\) the operating limit obtained from Eq. (7). Saturation temperature \(T\) is in Kelvin and \(T_c\) is the critical temperature of R-134a in K. \(\beta\) denotes the inclination with the vertical from 0\° to 90\°. A fit of the data of Fig. 5 yields \(b_1\) is \(-0.0125\pm/-10\%\) and \(b_2\) is \(1.01\pm/-10\%. Fit parameters \(F = 44\) and \(r^2 = 0.88\).
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are obtained. The two errors indicated in Eq. (10) are for a 95 % confidence interval. Extrapolation of the fit of Eq. (10) to temperatures outside the measured range (20°C – 75°C) should be done with prudence.

5. Conclusions

The operation limiting heat flux, \( q''_{\text{lim}} \), in a 3 m long, R-134a filled thermosyphon, with \( L/D \) ratio 188, has been assessed in a wide operating range. The dependencies of \( q''_{\text{lim}} \) on filling ratio, angle of inclination and saturation temperature have been determined. Knowledge of these limits is essential for design of heat exchangers equipped with thermosyphons. Maximum heat fluxes at the evaporator of 24 kW/m\(^2\) have been measured, corresponding to heat transfer rates of 1300 W.

The following new trends have been observed:

- The operation limiting heat flux decreased with increasing saturation temperature and with decreasing angle of inclination with the vertical.
- Proper functioning of the thermosyphon is observed up to angles of inclination of \( \beta = 83^\circ \).

Physical explanations for the trends observed have been presented.

A new correlation is proposed to take the effect of the angle of inclination on operation limiting heat flux into account. The new correlation predicts this operation limiting heat flux of a thermosyphon as a function of temperature dependent working fluid properties and geometry, including angle of inclination. Because of the accounting for the above trends and because they are based on existing correlations, the new correlations are also relevant for filling refrigerants other than R-134a.
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Figure 1
The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

Figure 2
The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

Figure 3
The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

Figure 4

Coolant flow = $2.83 \times 10^{-3} \pm 0.3 \times 10^{-3}$ [kg/s]

$\beta = 0^\circ$

$F_e$

+ 25%

○ 62%

▲ 100%
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Figure 5
The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

Figure 6
The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

Figure 7
The Effect of the Angle of Inclination on the Operation Limiting Heat Flux of Long R-134a Filled Thermosyphons

Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>- 3m</td>
</tr>
<tr>
<td></td>
<td>- Copper container</td>
</tr>
<tr>
<td>Diameter</td>
<td>- 16 mm (outer)</td>
</tr>
<tr>
<td></td>
<td>- Wall thickness 0.8 mm</td>
</tr>
<tr>
<td></td>
<td>- Smooth inner surface</td>
</tr>
<tr>
<td>Condenser</td>
<td>- $L_{\text{cond}} = 1.45$ m</td>
</tr>
<tr>
<td></td>
<td>- Tap water cooling, Altometer 41BNW15 flow meter, flow rates of 0 – 0.18 ± 0.01 l/s. Coolant inlet and outlet temperatures measured with Pt-100 (IC Istec ME 1009) sensors. Better than 0.1°C accurate between 0 – 100°C.</td>
</tr>
<tr>
<td></td>
<td>- Coolant inlet temperature adjustable with preheater</td>
</tr>
<tr>
<td></td>
<td>- 20 mm polyethylene foam insulation</td>
</tr>
<tr>
<td></td>
<td>- 4 K-type thermocouples at outer wall, 0.75 °C accurate</td>
</tr>
<tr>
<td></td>
<td>- Intruding Pt-100 for saturation temperature measurements</td>
</tr>
<tr>
<td>Adiabatic section</td>
<td>- $L_{\text{ad}} = 0.35$ m</td>
</tr>
<tr>
<td></td>
<td>- 2 K-type thermocouples at outer wall, 0.75 °C accurate</td>
</tr>
<tr>
<td>Evaporator</td>
<td>- $L_{\text{evap}} = 1.20$ m</td>
</tr>
<tr>
<td></td>
<td>- Heated uniformly with electrical heater, maximum 1950 ± 1 W, controlled by a Gossen Wattmeter</td>
</tr>
<tr>
<td></td>
<td>- 40 mm glass wool insulation, heat losses 0.5% of the heat input at worst</td>
</tr>
<tr>
<td></td>
<td>- 6 K-type thermocouples at outer wall, 0.75 °C accurate</td>
</tr>
<tr>
<td></td>
<td>- WIKA type RB manometer. 0 – 40 bar, 0.5 bar accurate</td>
</tr>
<tr>
<td>Working fluid</td>
<td>- R-134a</td>
</tr>
<tr>
<td></td>
<td>- Fluid inventory accurate to 0.1 g</td>
</tr>
</tbody>
</table>

Acknowledgments

The support of H. Hagens of VDL Klima bv., the Netherlands, in facilitating the experimental work is greatly appreciated.
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Nomenclature

\( A \)  \hspace{1cm} \text{surface area, m}^2

\( Bo \)  \hspace{1cm} \text{Bond number } \sqrt{\frac{\rho_f g d^2}{\sigma}}, -

\( Fe \)  \hspace{1cm} \text{filling degree, -}

\( Ku \)  \hspace{1cm} \text{Kutateladze number } (0.14 \pm 0.01) \left(1 - \frac{T_{ad}}{T_c}\right)^{\frac{1}{6}} Bo^{\frac{1}{2}} \left(\frac{d}{L_{evap}}\right)^{0.92} \left(1 + \left(\frac{\rho_a}{\rho_l}\right)\right)^{-\frac{1}{4}}, -

\( L \)  \hspace{1cm} \text{length, m}

\( Q \)  \hspace{1cm} \text{heat flow rate, W}

\( T \)  \hspace{1cm} \text{temperature, °C}

\( V \)  \hspace{1cm} \text{volume, m}^3

\( cp \)  \hspace{1cm} \text{heat capacity at constant pressure, J/(kgK)}

\( d \)  \hspace{1cm} \text{diameter, m}

\( g \)  \hspace{1cm} \text{acceleration due to gravity, m/s}^2

\( \Delta h \)  \hspace{1cm} \text{fg enthalpy of evaporation, J/kg}

\( \dot{m} \)  \hspace{1cm} \text{mass flow rate, kg/s}

\( q'' \)  \hspace{1cm} \text{heat flux, W/m}^2

\( r \)  \hspace{1cm} \text{radius, m}

Greek

\( \beta \)  \hspace{1cm} \text{inclination angle to the vertical, °}

\( \rho \)  \hspace{1cm} \text{mass density, kg/m}^3

\( \sigma \)  \hspace{1cm} \text{surface tension, N/m}

Subscripts

\( ad \)  \hspace{1cm} \text{adiabatic}

\( c \)  \hspace{1cm} \text{critical}

\( cond \)  \hspace{1cm} \text{condenser}

\( evap \)  \hspace{1cm} \text{evaporator}
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f fluid
i inner
l liquid
lim limit
sat saturation
v vapour
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References


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Figure captions

Fig. 1: Schematic view of the experimental setup

Fig. 2: Temperature history at operating limit. Insert shows thermocouple positions

Fig. 3: Temperature history at operating limit at large inclination and high temperatures. See Fig. 2 for thermocouple positions.

Fig. 4: Operating limit of the thermosyphon vs. saturation temperature for various filling ratios, $A_{\text{evap}} = 0.0543 \text{ m}^2$. Evaporator heat flux scale is linear.

Fig. 5: Operating limit of the thermosyphon vs. inclination angle for various filling ratios and saturation temperatures, $A_{\text{evap}} = 0.0543 \text{ m}^2$.

Fig. 6: Proof of wetting of the adiabatic wall at inclination by a liquid film by drop impingement.

Fig. 7: Predicted operation limiting heat flux by correlations from literature, $\beta = 0^\circ$.

Table caption

Table 1: Main features of experimental setup