Experimental Validation of Two Simulation Models for Two-Phase Loop Thermosyphons

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ABSTRACT: Five two-phase closed loop thermosyphons (TLTs) specially designed and constructed for the present study are one small scale loop, two medium scale loops (MSL I and MSL II) and two large scale loops (LSL I and LSL II).

Two simulation models based on thermal resistance network, lumped and sectorial, are presented. In the Lumped model, the evaporator section is dealt as one lumped boiling section. Whereas, in the Sectorial model, all possible phenomena which would occur in the evaporator section due to the two-phase boiling process are considered in detail. Flow regimes, the flow transitions between flow regimes and other two-phase parameters involved in two-phase flows are carefully analyzed.

In the present study, the results of two different simulation models are compared with experimental results. The comparisons showed that the simulation results by the Lumped model and by the Sectorial model did not show any partiality for the model used for the simulation. The simulation results according to the correlations show the various results in the large different range.

Nomenclature

A	: surface area [m^2]
Bo	: Boiling number, $q/(\rho h_{fg})$
c_{pl}	: specific heat [kJ/kgK]
D	: diameter [m]
F	: frictional parameter
F_K	: constant determined by working fluid
g	: gravitational acceleration [m/s^2]
G	: mass velocity [kg/m^{2}s]
h	: heat transfer coefficient [W/m^{2}K]
h_{fg}	: latent heat of evaporation [J/kg]
k	: thermal conductivity [W/mK]
l	: length [m]
LSL	: large scale two-phase loop thermosyphon
MSL	: medium scale two-phase loop thermosyphon
Nu	: Nusselt number, hD/k
P	: pressure [Pa]
Pr	: Prandtl number, $\mu c_p/k$
Q	: heat transfer rate [W]
R	: thermal resistance [℃/W]
Re	: Reynolds number, $\mu u D/\rho$
SSL	: small scale two-phase loop thermosyphon
t	: temperature [℃]
Δt_{h-c}	: temperature difference between the heater and air [℃]
TLT	: two-phase loop thermosyphon
u	: velocity of air [m/s]

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U : overall heat transfer coefficient [W/m^{2}K]
V : volume [ml]
WF : working fluid
x : vapour quality
X_{tt} : Lockhart-Martinelli parameter

Greek symbols

$\forall$: void fraction
: : viscosity [kg/ms]
ν : kinematic viscosity [m^2/s]
ρ : density [kg/m^3]
Φ : surface tension [N/m]

Subscripts

∞ : evaluation at free stream conditions
ann : annular flow regime
c : condenser section
$cond$: condensation
$conv$: convection
ev : evaporator section or heated zone
h : heater
l : liquid, unit length
sat : saturation
T : total
tp : two phase flow
WF : working fluid

1. Introduction

In a two-phase loop thermosyphon (TLT), the continuous two-phase process of a working fluid in the loop utilizes the latent heat of vaporization to transfer heat from the heat source (the evaporator) to the heat sink (the condenser), positioned at different levels with a small temperature difference. Although there are many experimental and analytical studies on TLTs in the literature, most of them are limited to one or two particular systems of different geometry and size. The heat transfer performance of a TLT as a cooling system depends on the dimensions, geometry and materials of the evaporator, transporting tube and condenser sections, in addition to the shape, number of fins and air flow rates of the condenser and/or evaporator section, thermophysical properties of the working fluid and the contact resistance between the heat transfer surface of the interest and the evaporator/condensor section.

The main objectives of the present study, are experimentally and analytically to investigate the heat transfer characteristics of five (5) widely different scale TLTs, ranging between 60 and 100,000 watts, and to see if a computer simulation alone for such TLT heat transfer systems would give any meaningful quantitative results without being accompanied with some benchmark experimental verification. Several different fluids were used as a working fluid. The lumped and the sectorial thermal resistance methods are used for the numerical simulation.

There have been many attempts to simplify, in the analysis for the two-phase flow and heat transfer processes in a TLT system, to avoid the complexity and uncertainty of the flow patterns of the two-phase flow involved. In general, the heat transfer of a two-phase flow depends on a great number of different factors: heat flux, pressure, mass flow rate, quality, void fraction, thermal properties of liquid and TLT material, surrounding physical geometry, and others. This fact, together with a great number of different two-phase flow patterns, hinders the construction of an adequate physical method of the process.

In the computer simulation of a two-phase flow/heat transfer system, such as TLTs, a large number of empirical correlations are needed which present many complications in the effort to simulate the two-phase system.

The first difficulty encountered is that some of the available correlations for various heat transfer coefficients has to be used for the conditions beyond the range of variables over which they are established. For an example, even if there are numerous investigations on heat transfer coefficients such as boiling, condensation and forced convection over finned surfaces, most, if not all, of them are empirical. This implies that even though a computer simulation may predict the most of the parameters involved, provided that correct empirical correlations are used, to do so, the interior temperature distribution must be verified by experiment.

The second difficulty, especially for the sectorial model, is to determine the best method for handling the transition regions between the various flow regimes occurred in the evaporator section. Various parameters such as velocity, void fraction and quality are to be used to determine the transition regions.

The third is that the pressure drop along a TLT must be analysed to have the entire simulation program converged. The equations which are used in the calculation for the pressure drop have the same difficulties related to the two difficulties as mentioned above.

In the present paper, the simulation of TLT systems by two simulation models, i.e., Lumped and Sectorial, are compared with the experimental results from 5 TLTs of very different size.

2. Two simulation models: Lumped and Sectorial

The goal of any simulation study for a mechanical system is to provide the capabilities to predict many variables which would affect the performance of the system under different operating conditions with the least amount of cost. The simulation for a Two-Phase Thermosyphon system can not be any exception.

For a loop two-phase thermosyphon, especially because of the flow boiling in the evaporator section, two simulation models based on thermal resistance network can be considered, namely, Lumped and Sectorial (or Flow Pattern) models. The major difference is how to manage the simulation procedure for the section between the evaporator and the condenser inlets. As stated above, a purely analytical solution for Two-Phase Loop Thermosyphon (TLT) systems is not possible at the moment because of the closure problems of the governing differential equations.

As illustrated in Fig. 1, the Lumped model does not consider different flow patterns which would exist in the section and assumes two-phase flow in the evaporator section of a TLT as one lumped boiling section, i.e., one empirical equation for a forced convective boiling. This model is very attractive because it attempts to simulate the chaotic phenomenon of the evaporator in a TLT system by one lumped heat transfer mode. However, it is obvious that the lumped model could not simulate the Two-Phase Thermosyphon adequately because of its simplistic approach to cover all the heat

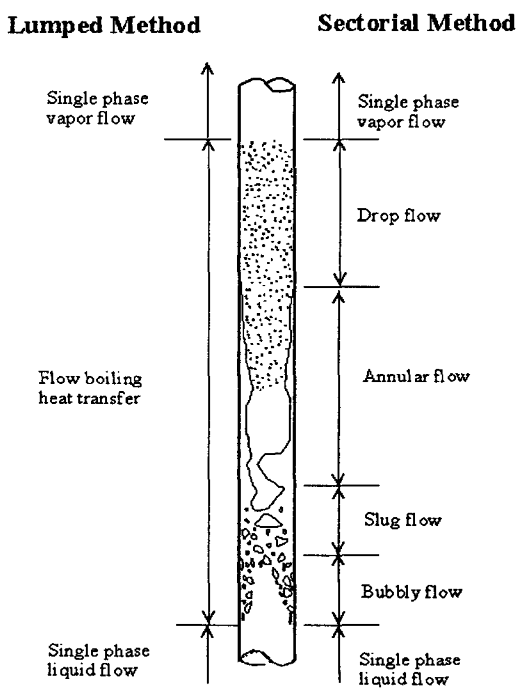


Fig. 1 Two simulation models.

transfer modes of the different flow regimes involved in the system by one equation.

On the other hand, the Sectorial model is built on the flow regimes of the two-phase flows involved within the system because the heat transfer in the evaporator section of a TLT is that of flow boiling. All possible phenomena which would occur in the evaporator section due to the two-phase boiling process are considered in detail in the Sectorial model. Flow regimes (bubbly, slug, churn, annular and annular mist etc.), flow transition between flow regimes and other two-phase parameters involved in a two-phase flow must be systematically analysed. The governing equations for computer simulation models in the present study are briefly given in the following.

Mass conservation:

$$\frac{d\dot{m}}{dy} = 0 \tag{1}$$

Momentum conservation:

$$-\frac{dp}{dy} = \left(\frac{dp}{dy}\right)F + G^2\frac{d}{dy}\left\{\frac{(1-x)^2}{\rho_l(1-\alpha)} + \frac{x^2}{\rho_g\alpha}\right\} + g\sin\theta\left[\alpha\rho_g + (1-\alpha)\rho_l\right] + \left(\frac{dp}{dy}\right)_{mis.} \tag{2}$$

Enegy conservation:

$$\frac{Q}{GA} = \frac{dH}{dy} \tag{3}$$

The total thermal resistance of a two-phase thermosyphon, be it closed or loop, may be written as:

$$R_T = \frac{1}{UA} = \sum R_i \tag{4}$$

and the total heat transfer rate is:

$$Q = \frac{\Delta t_{h-c}}{R_T} \tag{5}$$

However, the constituent thermal resistance for a given TLT is quite unique for that particular system. Examples of the thermal resistance net works for TLTs are given by Rhi and Lee.[1] The main thermal resistances of interest among all the constituent resistances for a given TLT for the simulation are: the thermal resistance of the evaporation, R_{ev}, the thermal resistance of the condensation, R_{cond}, and the thermal resistance of the forced convection to the condenser section, R_{conv}.

Both Lumped and Sectorial simulation models which are based on the thermal resistance network require number of empirical correlations for various heat transfer coefficients as mentioned previously. Various correlations which required to simulate a TLT are listed in Table 1 to 3. All appropriate empirical correlations for flow boiling (Table 1), h_{ev}, condensation (Table 2), h_{cond}, forced or free convection (Table 3) from finned surfaces, h_{conv} and the equations of fin efficiency must be collected and evaluated for its applicability.

For the Lumped numerical model, 10 different correlations for the forced convection vaporization, h_{ev}, proposed by Schrock & Grossman,[2] Ananiev et al.,[3] Wright,[4] Chen,[5] Pujol & Stenning,[6] Crain & Bell,[7] Shah,[8] Gungor & Winterton,[9] Kandlikar[10] and Sekoguchi et al.[11] were used in the simulation. For the condensation heat transfer coefficient, h_{cond}, many empirical correlations for the condensation such as those of Nusselt,[12] Rohsenow,[13] Smirnov & Lukanov[14] were tried. For the heat transfer coefficient for the condensation section, h_{conv}, 3 empirical correlations of Knudsen & Katz, Fand and Churchill & Bernstein quoted by Holman[12] were used.

For the Sectorial model, the thermal resis-

Table 1 Two-phase heat transfer coefficient correlations for Lumped model

#	Author	Correlations
1	Schrock and Grossman[2]	$\frac{h_{tp}}{h_l}=a_1\left\{\mathrm{Bo}+a_2\left(\frac{1}{X_{tt}}\right)^{b_1}\right\}^{b_2}$ $a_1=7.39,\ a_2\times10^{-3}=1.5,\ b_1\times10^4=0.67,\ b_2=1$
2	Ananiev[3]	$h_{tp}=h_l\left(\frac{\rho_l}{\rho_{av}}\right)^{0.5}$
3	Wright[4]	$\frac{h_{tp}}{h_l}=a1\left\{\mathrm{Bo}+a2\left(\frac{1}{X_{tt}}\right)^{b1}\right\}^{b2}$ $a1=6.7,\ a2\times10^{-3}=3.5,\ b1\times10^4=0.67,\ b2=1$
4	Chen[5]	$h_{tp}=h_{mic}+h_{mac}$
5	Pujol and Stenning[6]	$\frac{h_{tp}}{h_l}=a\left(\frac{1}{X_{tt}}\right)^b \quad a=4.0,\ b=0.37$
6	Crain and Bell[7]	$h_{tp}=0.0587\left(\frac{k_l}{D}\right)\mathrm{Re}_l^{0.85}\,\mathrm{Pr}^{0.4}\left(\frac{d}{D}\right)^{0.1}x^{-7.6}$
7	Shah[8]	$h_{tp}=\max\,[h_c,\ h_{nb}]$
8	Gungor and Winterton[9]	$\frac{h_{tp}}{h_l}=\left\{1+3000\,\mathrm{Bo}^{0.86}+\left(\frac{x}{1-x}\right)^{0.75}\left(\frac{\rho_l}{\rho_g}\right)^{0.41}\right\}$
9	Kandlikar[10]	$h_{tp}=h_l\left[C_1Co^{C_2}(25\mathrm{Fr}_{le})^{C_5}+C_3\mathrm{Bo}^{C_4}F_K\right]$ $Co=\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}$
10	Sekoguchi[11]	$\frac{h_{tp}}{h_l}=a\left(\frac{1}{X_{tt}}\right)^b$

Table 2 Condensation heat transfer coefficient correlations

#	Author	Correlations
1	Nusselt[12]	$h_{cond}=\left[\frac{k_l^3\rho_l(\rho_l-\rho_g)gh_{fg}}{\mu_l\Delta t_{sat}l_c}\right]^{1/4}$
2	Rohsenow[13]	$h_{cond}=0.943\frac{k_l}{l_c}\left[\frac{l_c^3\rho_l(\rho_l-\rho_g)g}{\mu_l\Delta t_{sat}k_l}(h_{fg}+0.68c_{pl}\Delta t_{sat})\right]^{1/4}$
3	Smirnov and Lukanov[14]	$h_{cond,f}=0.689\left(\frac{k_l^3\rho_l^3gh_{fg}}{\mu_l\Delta t D_{eq}}\right)^{1/4}$

Table 3 Forced and natural convection correlations

#	Author	Correlations
1	Knudsen and Katz[12]	$\frac{hD}{k_f}=C\left(\frac{u_\infty d}{\nu_f}\right)^n\mathrm{Pr}^{1/3} \quad C=0.683,\ n=0.466 \text{ for } 40<\mathrm{Re}<4000$
2	Fand[12]	$\mathrm{Nu}_f=(0.35+0.65\mathrm{Re}_f^{0.52})\mathrm{Pr}_f^{0.3}$
3	Churchill and Bernstein[12]	$\mathrm{Nu}=0.3+\frac{0.62\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}}{[1+(0.4/\mathrm{Pr})^{2/3}]}\left[1+\left(\frac{\mathrm{Re}}{282{,}000}\right)^{5/8}\right]^{4/5}$

Table 4 Heat transfer coefficient correlations for annular flow

Author	Correlations
Rhee and Young[15]	$\frac{h_{ann}}{h_l}=59.03\left(\frac{1+x}{1-x}\right)^{0.81}Fl^{0.3}\quad Fl=Gh_{fg}/q$
Lavin and Young[16]	$\frac{h_{ann}}{h_l}\left(\frac{\dot{m}h_{fg}}{q}\right)=C_2\left(\frac{1+x}{1-x}\right)^{1.16}$

tance of the evaporator section must be determined through various flow regimes involved. In order to calculate the heat transfer, the pressure drop, and the void fraction in a TLT, it is necessary to subdivide the loop into a number of short elemental lengths, along which the local values of the pressure gradient, heat flux, etc. are calculated. In a TLT, virtually every and all possible modes of two-phase flow and heat transfer can be considered but in the present study, the evaporator section were divided in 6 different flow regimes as illustrated in Fig. 1 and the various empirical correlations for heat transfer coefficient and void fraction for each flow regime and for the flow regime transition criteria were collected and used in the simulation.[15] Except for the heat transfer coefficient correlation of annular flow, other parameters are fixed to one correlation. For the heat transfer coefficient correlations of annular flow, correlations by Rhee & Young[15] and Lavin & Young[16] were tried for the simulation of Sectorial model. These correlations are shown in Table 4.

The simulation logics for both Lumped and Sectorial models are that the two-phase flow inside loop should satisfy mass, energy, and momentum balances. And the simulation program converges to satisfy the condition that total pressure drop summation should be zero ($\sum \Delta P=0$). The simulation program would estimate an initial pressure and temperature in the evaporator liquid inlet port and the mass flow rate of the TLT loop, then proceed to calculate the heat transfer, the exit state of the working fluid and the fluid temperature downstream of the evaporator. The pressure drop across and the heat loss along the section between the evaporator and condenser sections are calculated. Assuming a negligible pressure drop along the condenser section, and by knowing the inlet and the exit states of the condenser, the heat transfer in the condenser and the temperature of the fluid leaving the condenser section is calculated. The inlet pressure of the evaporator section is varied until the incoming liquid temperature is achieved. Once this convergence is reached, an energy balance applied to the evaporator section would yield a new value for the fluid temperature at the inlet port of the evaporator section. This new value is used to generate the final values.

The thermal properties of working fluids are formulated into empirical equations using a data regression for the temperature range of −50℃ to 300℃. The analysis of these equations for the thermal properties of each working fluid showed the difference of about ±5%.

In a TLT, there can be two types of performance limits, i.e., the dry-out crisis at very low liquid fill charges and the burn-out crisis for relatively large liquid fill charges. However, this is the beyond the scope of the present study and will not be discussed here.

3. Experimental

To verify the present simulation study, 5 different size two-phase loop thermosyphones (TLT) were used in the experimental program, i.e., one small, two medium and two large scale TLTs as indicated in Table 5. The sizes of

Table 5 Test two-phase loop thermosyphons

Two-phase loops	Abbreviated designation	Heat transfer surface area (m^2)	Max. heat transfer rate (W)	Application
Small scale loop	SSL	0.00123	150	Cooling of electronic elements
Medium scale loop	MSL I	1.53 (Case 1) 0.89 (Case 2)	60	Heat extraction from enclosed spaces
	MSL II	0.019	1500	Basic loop
Large scale loop	LSL I	0.095	7500	Waste heat recovery system
	LSL II	3.31	100000	Waste heat recovery system

TLTs are classified by the size of the evaporator and the heat transfer rates. The small scale TLT was for the cooling of MCM (multichip module), the medium scale TLTs for heat extraction systems and the large scale TLTs for waste heat recovery systems. The details of the five TLTs can be found elsewhere.[17]

The heat transfer rate was calculated from the power measurements or the energy balance made on the systems. The heat losses through the insulation of the heating and evaporation section were seen negligible because of the good insulation of the heating and the evaporator sections. The errors involved in the calculation of the heat transfer coefficient were generally due to the inaccuracy of the temperature and the power measurements. Even if the readings of the power and the temperatures were recorded after the steady state has been reached, a small fluctuation was observed (± 0.2 V for voltage, ± 0.01 A for current and ± 0.2℃ for temperature).

4. Comparisons between simulation and experiment

The comparisons between the experimental and the corresponding simulated results with both the Lumped and Sectorial models for the five TLTs (SSL, MSL I, MSL II, LSL I and LSL II) are made and they are represented in Figs. 2 to 6 where the line plots represent the simulated results.

The success of the computer simulation based on the thermal resistance network models depends on the choice of empirical correlations for various thermal resistances. For the Lumped model in the present study, we have considered 10 empirical correlations for the flow boiling heat transfer coefficients (h_e), 3 for the condensation (h_c), and 3 for forced convection (h_{conv}) for a TLT. Thus, we obtained as many as 90 possible solutions for a given condition from the simulation. It is obvious that every one of them could be the right one. The focus of present simulation study is given on the effects of heat transfer coefficient correlations. Therefore, if our simulation study were to consider the effects of other two-phase flow parameters such as the pressure drop, the void fraction, and others, the simulation results would be innumerable.

Figures 2 to 6 show only the simulation results with different flow boiling heat transfer correlations, with a fixed condensation and convection heat transfer correlations. It can be seen in Fig. 2 to 6 that there are large differences among the simulation results based on the different correlations of flow boiling heat transfer coefficients. Because the solution was based on the thermal resistance network model, the key to check the correctness of the simulation is to compare the temperature distributions within a TLT, obtained by the simulation with that of experiments. The simulated interior temperature

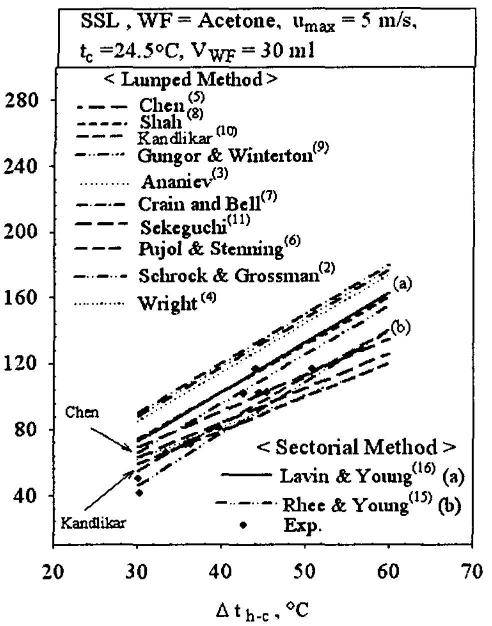


Fig. 2 Comparison between experiment and simulation with various correlations for h_{tp}, small scale TLT, Q=150 watts.

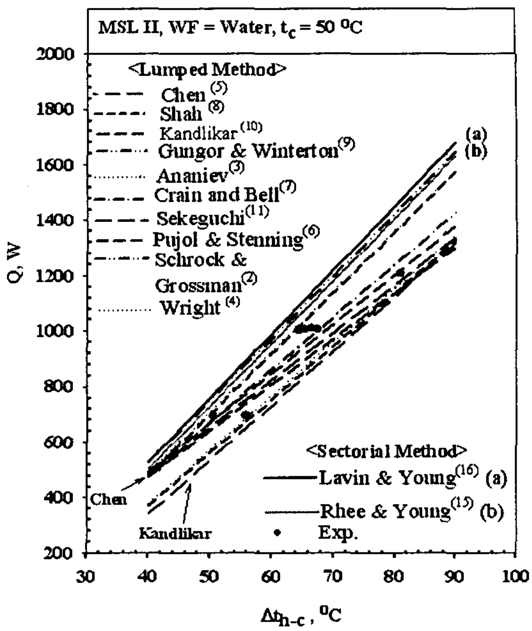


Fig. 4 Comparison between experiment and simulation with various correlations for h_{tp}, medium scale TLT II, Q=1,500 watts.

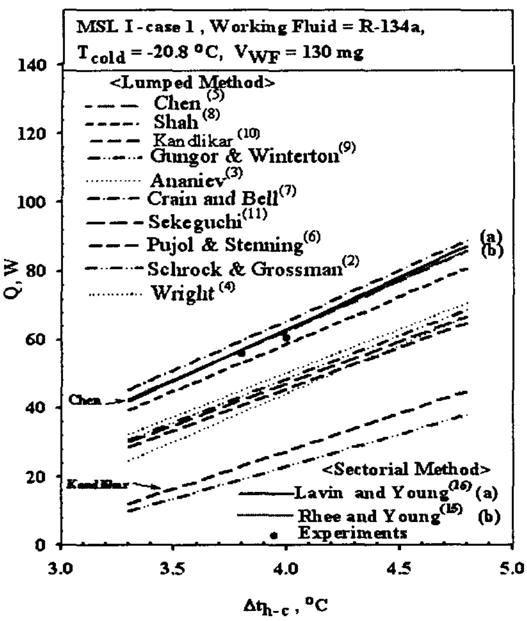


Fig. 3 Comparison between experiment and simulation with various correlations for h_{tp}, medium scale TLT I, Q=60 watts.

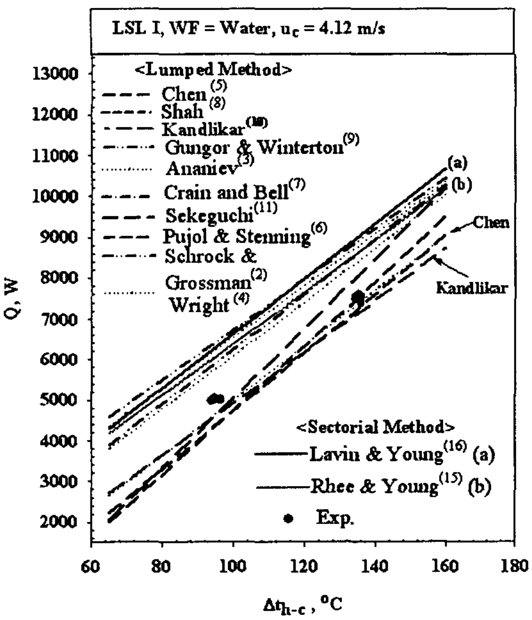
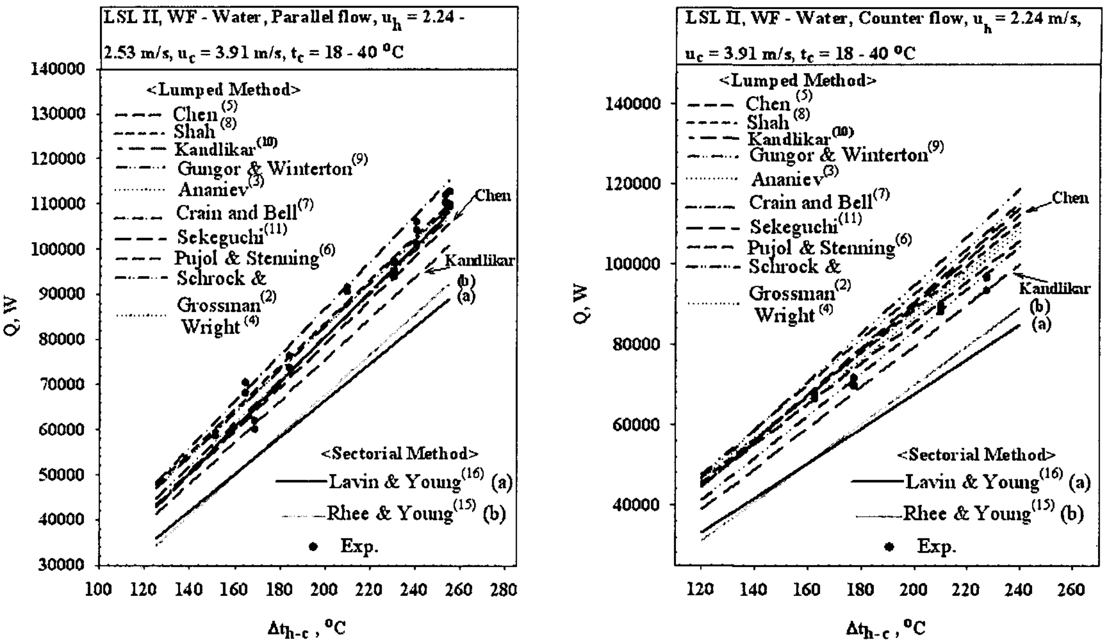


Fig. 5 Comparison between experiment and simulation with various correlations for h_{tp}, large scale TLT I, Q=7,500 watts.



(a) Parallel flow

(b) Counter flow

Fig. 6 Comparison between experiment and simulation with various correlations for h_{tp}, large scale TLT II, Q=100,000 watts.

distributions could be quite different from the experimental results, depending on the choice of the empirical correlations used for boiling and condensation even if the heat transfer rates obtained by the simulation are in good agreement with the corresponding experimental results. To obtain the best agreement between the experimental and simulation results which are physically correct, some modification to this approach must be done.

To modify a given combination of the boiling and condensation heat transfer correlations, the method suggested by Park[18] may be used for the heat transfer coefficients for both the evaporator and the condenser sections. Since the modified correlations of the boiling and the condensation heat transfer coefficients are physically correct, it is possible to use the simulation for the various parameters which affect a TLT.

Figs. 2 to 6 for Q vs. Δt_{h-c} of the five TLTs of the present study show large differences between the experimental results and those of the simulation. It is seen that each correlation of h_{tp} generates a definite relationship for a given condition, implying that it is necessary to find a satisfactory correlation for a given condition or, at least, some modification of an existing correlation must be made as discussed above. The largest differences can be found in the cases for SSL (Fig. 2) and MSL I (Fig. 3), and the main reason for this may be due to the fact that the correlations used in the simulation are originally developed for large scale two-phase systems such as nuclear reactors or industrial re-boilers. The test environmental conditions of the various empirical correlations used in the present simulation study are all different from each other. It is seen in the figures that the simulation results with the empirical correlations for the two phase flow heat transfer, h_{tp}, of Chen,[5] Shah[8] and Kandlikar[10] for the

Lumped model and that of Rhee and Young[15] for the annular flow regime in the Sectorial model show the best agreement with the experimental results. The results of Chen[5] and Kandlikar[10] for the Lumped model and that of Rhee and Young[15] for the annular flow regime in the Sectorial model were indicated in figures. In these simulation, the heat transfer coefficient for condensation, h_{cond}, of Nusselt[12] and the forced convection heat transfer coefficient, h_{conv} of Knudsen[12] were chosen as the fixed parameters. For the case of MSL I (Fig. 3) where the combination of the heat transfer coefficients, h_{tp} of Chen,[5] h_{cond} of Nusselt and h_{conv} of Knudsen gave the best agreement. For the case of MSL I, because of the peculiar condenser geometry which is quite different from those of other TLTs, the condensation heat transfer coefficient correlation, h_{cond}, developed by Smirnov and Lukanov[14] was used.

Even though the comparison for the large scale TLTs by the lumped model show better agreements between the experiment and simulation than those for the cases of SSL (Fig. 2) and MSL I & II (Figs. 3 & 4), the simulation results by the Lumped model and by the Sectorial model did not show any partiality for the model used for the simulation. The simulation results with the Lumped model vary widely depending on the choice of h_{tp}, but with the Sectorial model, the present combination of h_{tp}, h_{cond} and h_{conv} given above placed the agreement between the simulation and experiment within an acceptable range except for LSL II. Generally, it was noticed as far as the present study is concerned that the simulation by the Lumped model gave reasonable agreements for the large scale TLTs with the selected correlations of, Chen,[5] Shah[8] and Kandlikar[10] whereas the simulation by the Sectorial model gave reasonable agreements for SSL, MSL, and LSL I within an acceptable error range as seen in Figs. 2 to 5, but not for LSL II as seen in Figs. 6.

It is clearly seen in the simulation, regardless of the models used, that a computer simulation alone can not give any meaningful quantitative results unless it is validated by some experimental results. Therefore computer simulation should be developed with a benchmark experimental verification when two-phase flow and heat transfer are involved. The study also shows that the simulation results by the Lumped model and by the Sectorial model did not show any strong partiality for the model used for the simulation.

5. Concluding remarks

The simulation study by the two models, Lumped and Sectorial, on five TLT systems of very different size are discussed with the experimental results carried out. The limitation of the computer simulation for such two-phase heat transfer systems is noted. The present study strongly indicates that a computer simulation alone could not, at the moment, give any meaningful quantitative results unless it is accompanied with some experimental results for a system involving some empirical correlations. The comparisons between the experiment and the simulation results without any modification to the many empirical correlations needed in the simulation do not agree well especially with the experimental results from the smaller scale loops. This could be that the correlations used in the simulation are basically developed for large scale heat transfer systems involving two-phase flow.

The study shows that the simulation results by the Lumped model and by the Sectorial model did not show any strong partiality for the model used for the simulation. However, it is preferable to use the Lumped model for the simulation of a TLT because it does not require the complexity of the Sectorial model.

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