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The Optimization of Thickness and Permeability of Wick Structure with Different Working Fluids of L-Shape Heat Pipe for Electronic Cooling

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Abstract

As part of the ongoing research on finned L-shape heat pipes for electronic cooling, the present work focuses on the optimization of the thickness and permeability of wick structure of L-shape heat pipe, using different working fluids. D-Optimal Designs Software is used to obtain the optimal solution to align the competing parameters such as the working fluid properties, thickness of the wick and the type of wick structure. The optimization results yielded that a wick thickness of 0.52 mm and permeability of 1.39E-11 m^2 with water as a working fluid could produce the minimum temperature difference between the evaporator and condenser sections of 9.56 °C and liquid pressure drop of 5730 Pa, which could increase the heat transport capability from 35 W to 43 W. These results reveal that the performance of L-shape heat pipe in terms of heat transport capability is improved by 20%.

Keywords: *L-Shape Heat Pipe; D-Optimal Designs; Wick Structure; Working Fluid*

1. Introduction

The electronic devices have highly integrated circuits with an ever increasing power dissipating high heat flux which leads to an increase in the operating temperature of devices; this results in shortening the life time of the electronic devices [1]. Consequently, the need for cooling techniques to dissipate the associated heat is quite obvious. It is highly desirable to explore high-performance cooling devices, especially for CPU cooling. Thus, heat pipes are regarded as a promising way for cooling the electronic equipment. As an alternative to the traditional heat sinks, two-phase cooling devices, such as heat pipe and thermosyphon, have emerged as promising heat transfer devices; the effective thermal conductivity of a heat pipe can be 10 to 200 times more than that of a solid copper rod of the same diameter [2].

Substantial numerical and experimental works have been reported on the application of heat pipes [3-6]. Park [7] presented a numerical model of heat pipe for optimum placement of satellite equipment to predict the temperature profile by assuming cylindrical two-dimensional laminar flow for vapor, and conduction heat transfer for wall and wick. Noh and Song [8] focused on heat pipe with multiple heaters to predict the characteristics on transient heat pipe operation. Xie *et al.* [9] presented the applications of heat pipes in the portable computers, and their use was illustrated in Pentium processor-based notebooks and sub-notebooks. Xie *et al.* [10] summarized the future outlook of using the heat pipe for cooling personal computers, through reviewing the performance of several heat pipes with different designs and the new technology used for cooling personal computers. Seok-Hwan *et al.* [11] studied experimentally a new woven-wire-type wick for Miniature Heat Pipes (MHP), which had a high productivity and a large capillary limit. They used MHP with diameters of 3 mm or 4 mm which could be used for notebook- CPU cooling. Wuttijumnong *et al.* [12] reviewed the various cooling solutions using heat pipe and vapor chamber for cooling high power processors in a confined space of the notebook.

Recently, heat sinks with finned U-shape heat pipes have been introduced for cooling the high-frequency microprocessors such as Intel Core 2 Duo, Intel Core 2 Quad, AMD Phenom series and AMD Athlon 64 series [13]. The work of Wang *et al.* [14], Wang [15], Liang & Hung [13] and Elnaggar *et al.* [16] were remarkable contributions to finned U-shape heat pipes where they have been introduced to cooling the high-frequency microprocessors.

Recently, [17] and [18] have exerted effort to optimize the operating conditions such as heat input and the cooling air velocity without addressing the internal parameters of the heat pipe such as the working fluid properties, thickness of the wick and the type of wick structure.

The decrease in the pore size of the wick causes low wick permeability, which increases the maximum capillary pumping head generated by the wick to overcome the total pressure drop within the heat pipe. On the other hand, the

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permeability should be large in order to have a small liquid pressure drop and, therefore, a higher heat transport capability. Furthermore, the effective thermal conductivity in the liquid-wick region also plays an important role in the heat pipe performance as the high value of this parameter gives a small temperature drop across the wick, which increases the thermal performance of the heat pipe. The rate of mass transfer increases with the increase in thermal conductivity and porosity, while it decreases with the increase in viscosity [19]. The effective thermal conductivity in the liquid-wick region depends on the material of the wick structure, the working fluid properties, the thickness of the wick and the type of wick structure. These parameters present conflicting properties in most wick designs. Accordingly, an optimal wick design requires harmonization between these contradictory features.

Therefore, in the present study, D-Optimal Designs Software is used to obtain the optimal solution to align the competing parameters such as the working fluid properties, the thickness of the wick and the type of wick structure. The three significant parameters, wick thickness, wick permeability, and working fluids, are considered, in this study, with the objective of minimizing the temperature difference between the evaporator and condenser sections (ΔT) and liquid pressure drop ΔP_l to get the best performance of the heat pipe.

2. Materials and Methods

2.1. L-Shape Heat Pipe

As shown in Figure 1, the finned heat pipe under investigation serves to cool the CPU of a modern notebook. In this system, the heat pipe is used to transfer heat from CPU to the fins in a remote location, usually in the sides or corners of the notebook PC. The copper base plate directly communicates with the evaporator section of the heat pipe while the condenser section is equipped with 50 rectangular fins of 20mm × 10 mm size [17]. The total length of the heat pipe is 212 mm (the length of evaporator, adiabatic and condenser sections are 30 mm, 110 mm and 72 mm, respectively). The system is supported by a radial fan with dimensions of 73 mm × 73 mm × 10 mm (width ×length × thickness).

The heat transfers from processor (CPU) to base plate then to the heat pipe and then to the fins, and the heat is dissipated to the surrounding area by a fan.

The thermal resistance of the heat pipe (Rhp) is:

$$R_{hp} = \frac{\Delta T}{Q} \quad \text{where} \quad \Delta T = T_e - T_c \tag{1}$$

where Te is the evaporator temperature and Tc is the condenser temperature and Q is the rate of heat transfer.

2.2. Simulation Results

This study is extend to the work of [17] and [20], which investigated the effect of the thickness and permeability of the wick structure on L-shape heat pipe performance using different working fluids. The applied heat was 35 W with coolant airflow rate of 6.5 m3/h. As shown in Figures 2 and 3, which were illustrated by [20], a good performance of heat pipe was achieved by employing water with 0.5 mm thickness of sintered copper powder (recorded the smallest temperature difference 9.8 °C) but the unfavorable high pressure (6563 Pa) resulted in a low heat transport capability at the liquid–wick region. Consequently, the current study resolved this issue by using the D-Optimal Designs software to obtain the optimal performance associated with a moderately low pressure in liquid-wick region to achieve the maximum heat transport capability.

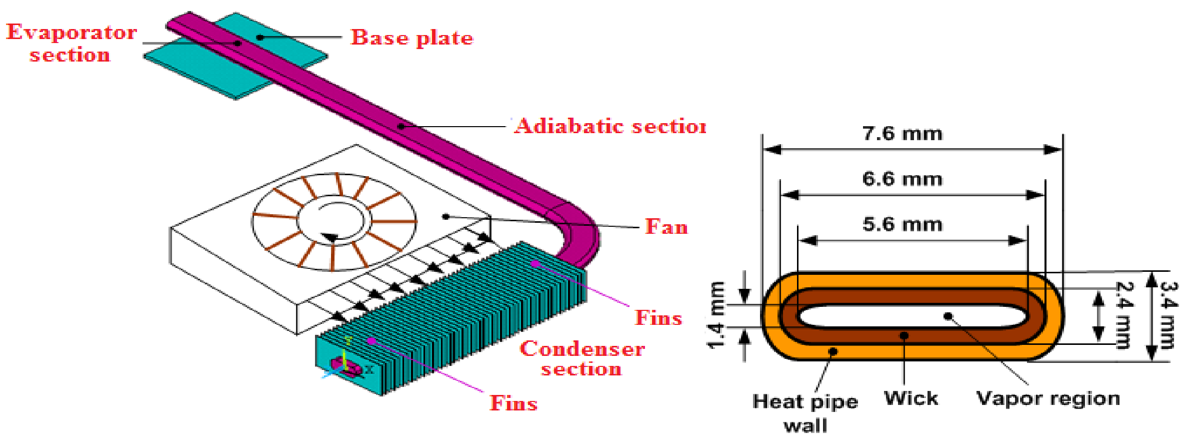


Figure 1. Finned flat heat pipe and its cross-section [17].

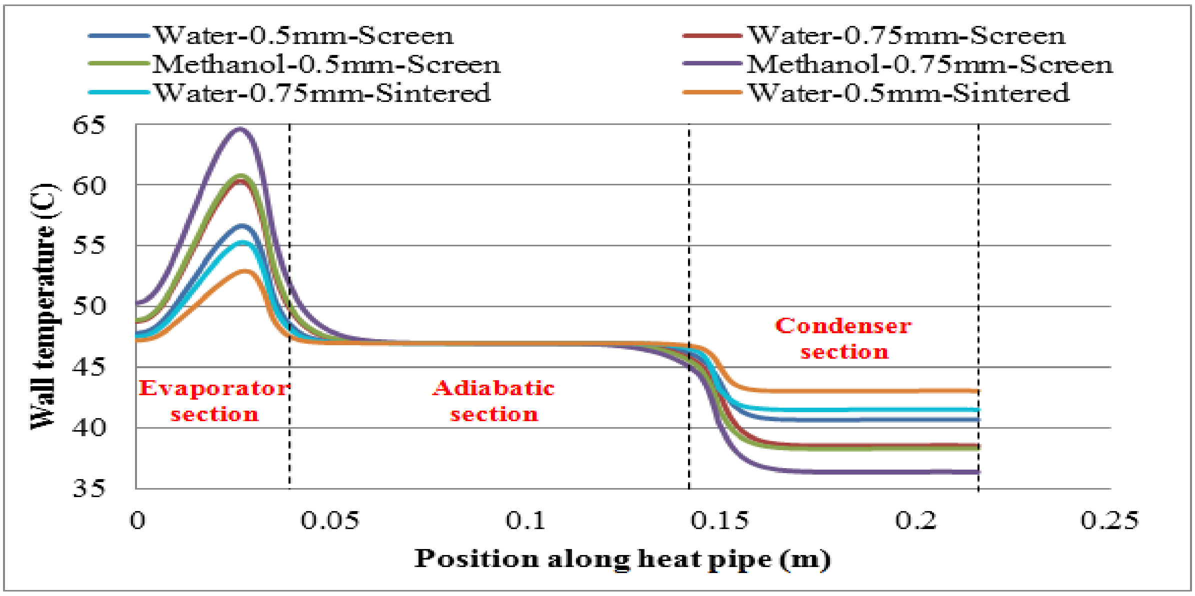


Figure 2. Wall temperature distribution along the heat pipe with various thicknesses and types of wicks and at different working fluids [20].

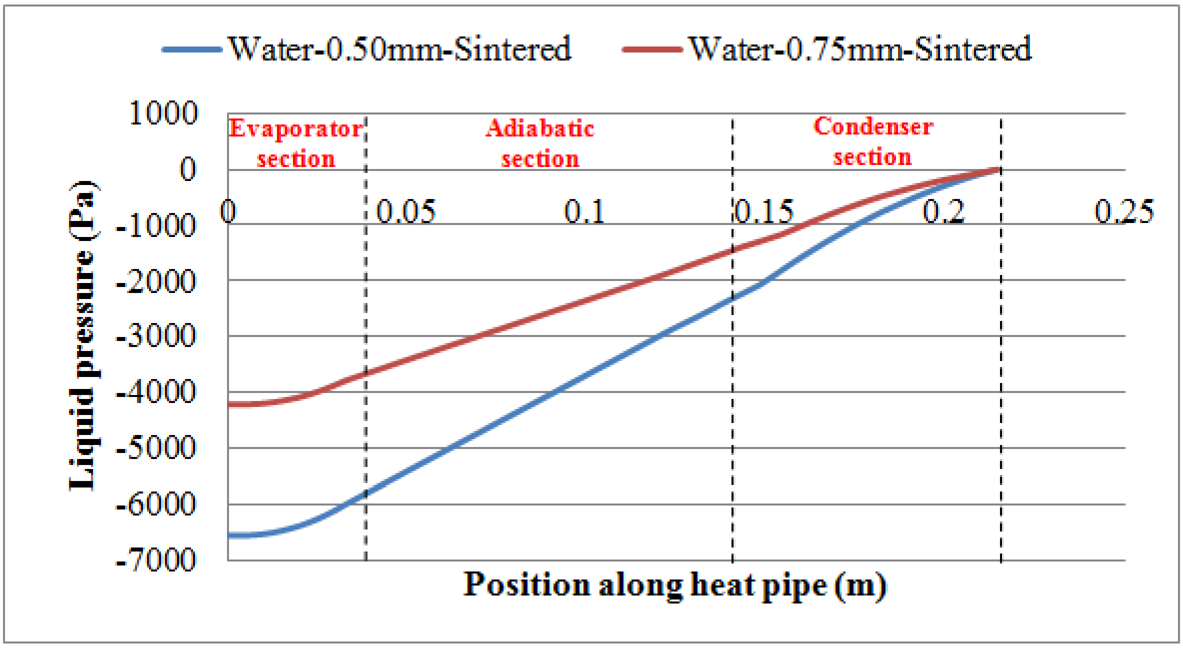


Figure 3. Predict liquid (Water) pressure distribution of heat pipe with sintered copper powder wick at various thicknesses [20].

2.3. Analytical method23

The maximum achievable heat transfer by the heat pipe can be obtained from the equation [21]:

$$Q_{max} = \left(\frac{\rho_l \sigma_l h_{fg}}{\mu_l}\right)\left(\frac{A_w K}{L_{eff}}\right)\left(\frac{2}{r_{eff}}\right) \qquad (2)$$

where μ_l = liquid viscosity, L_{eff} =effective length of the heat pipe, ρ_l = liquid density, K =wick permeability, A_w = wick cross-sectional area, h_{fg} = heat of vaporization of liquid, σ_l is surface tension and r_{eff} is the effective radius of the pores of the wick.

The properties of the working fluid change as follows:

$\rho_l = 989\ Kg/m^3$,

$\sigma_l = 0.066\ N/m$,

$\rho_v = 0.2\ Kg/m^3$ and

$h_{fg} = 2.4x10^6\ J/kg$

3. D-Optimal Designs

D-Optimal approach of Design of Experiment (DOE) software program is used for the design of experiments, statistical analysis, modeling and optimization. A D-optimal design is a computer aided design which contains the best subset of all possible experiments. Depending on a selected criterion and a given number of design runs, the best design is created by a selection process.

The optimality of a design depends on the statistical model and is assessed with respect to a statistical criterion, which is related to the variance-matrix of the estimator. Specifying an appropriate model and specifying a suitable criterion function require both an understanding of statistical theory and practical knowledge.

D-optimal designs for multi-factor experiments with both Numeric and Categorical factors are used. The factors can have a mixed number of levels. D-optimal designs are constructed to minimize the generalized variance of the estimated regression coefficients.

In this study, the analysis depends on the simulation results of Elnaggar [20] instead of experiments to obtain the optimal solution to align the competing parameters.

3.1. Factors Definition

This program was implemented based on the simulation results rather than the results of experiments. The three significant factors considered are: two numeric factors such as wick thickness (A) and wick permeability (B), and the categorical factor, working fluids (C), as presented in Table 1. Each factor is varied at two levels: low actual and high actual. Additionally, in this design, two response factors are used, such as the temperature difference between the evaporator and the condenser sections (ΔT) and the liquid pressure drop ΔP_l.

A total of 10 simulation runs were enhanced with 4 runs replications to assess the pure error, as illustrated in Table 2. Methanol with copper powder wick was excluded because it results in an exceedingly high pressure in the liquid-wick region.

4. Results and Discussion

4.1. Results of D-Optimal Designs

The model created for predicting the temperature differences between the evaporator and the condenser sections (ΔT) and the liquid pressure drops (ΔP_l) has been considered sensible. The final regression models, in terms of coded factors, are expressed by the following linear equations:

A. Water is used as working fluid

$$\Delta T = -2.22819 + 21.71200 * t_w + 3.91616 x 10^{10} * K \quad (3)$$

$$\Delta P_l = +8056.04799 - 3798.40 * t_w - 2.48759 x 10^{13} * K \quad (4)$$

B. Methanol is used as working fluid

$$\Delta T = +4.25681 + 21.71200 * t_w + 3.91616 x 10^{10} * K \quad (5)$$

$$\Delta P_l = +8611.04799 - 3798.40 * t_w - 2.48759 x 10^{13} * K \quad (6)$$

Where ΔT is the temperature difference between the evaporator and the condenser sections (°C), ΔP_l is liquid pressure in wick region (Pa), t_w is wick thickness (mm) and K is the wick preamability (m^2).

4.2. Interaction between Factors

Equations 3, 4, 5 and 6 are used to visualize the influences of factors (i.e., wick thickness and wick permeability) on temperature difference ΔT and liquid pressure drop ΔP_l as shown in Figure 4. For both working fluids, water and methanol, the curvature of 3D surfaces indicates that the wick permeability and wick thickness

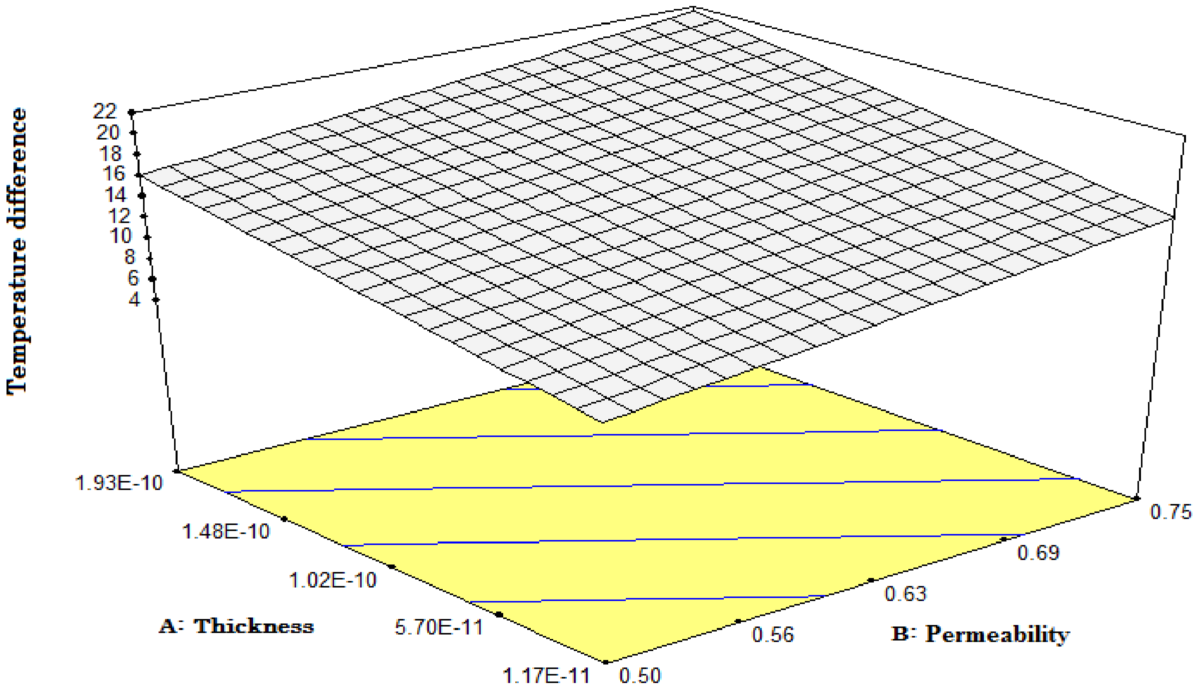
Table 1. Factors of D-Optimal design

Factor	Name	Units	Type	Low Actual	High Actual
A	Thickness	mm	Numeric	0.5	0.75
B	Permeability	m^2	Numeric	1.17E-11	1.93E-10
C	Working fluids		Categorical	Water	Methanol

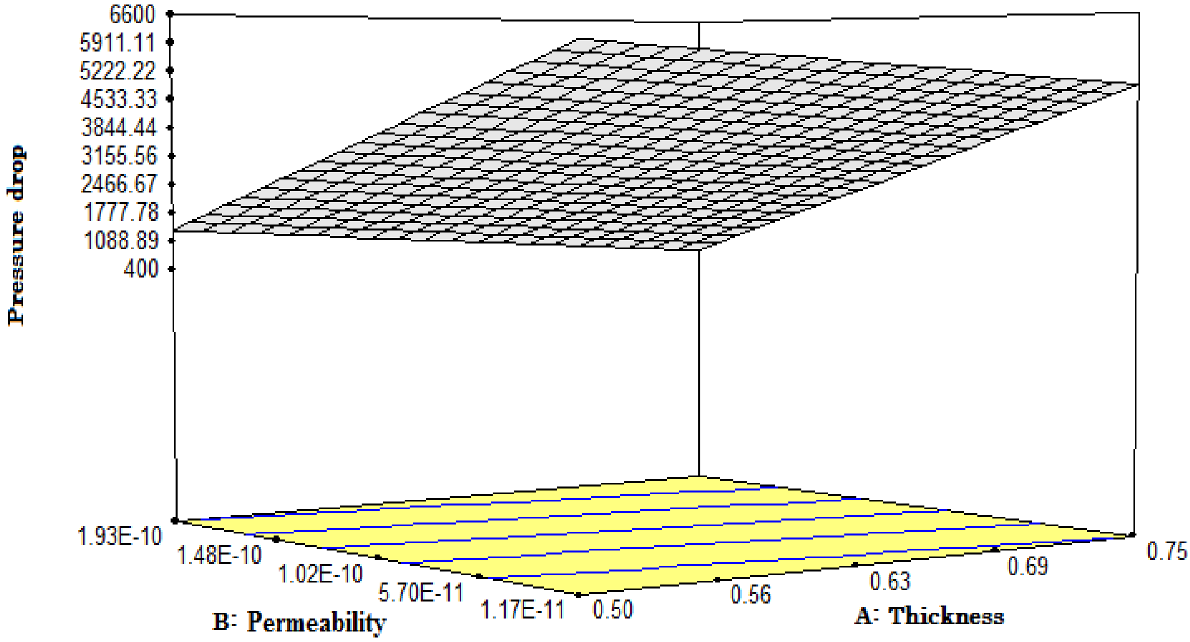
Table 2. Response values for different simulation conditions

Run no.	Factor 1 A:Thickness (mm)	Factor 2 B:Preamability (m^2)	Factor 3 C:Working fluids	Response 1 Temperature difference (°C)	Response 2 Pressure drop (Pa)
1	0.5	1.93E-10	Water	16	1129
2	0.5	1.93E-10	Water	16	1129
3	0.5	1.17E-11	Water	9.8	6563
4	0.5	1.93E-10	Methanol	22.5	1789
5	0.75	1.93E-10	Water	21.8	633
6	0.75	1.93E-10	Methanol	28.27	1083
7	0.75	1.17E-11	Water	13.8	4219
8	0.75	1.93E-10	Methanol	28.27	1083
9	0.75	1.93E-10	Water	21.8	633
10	0.5	1.93E-10	Methanol	22.5	1789

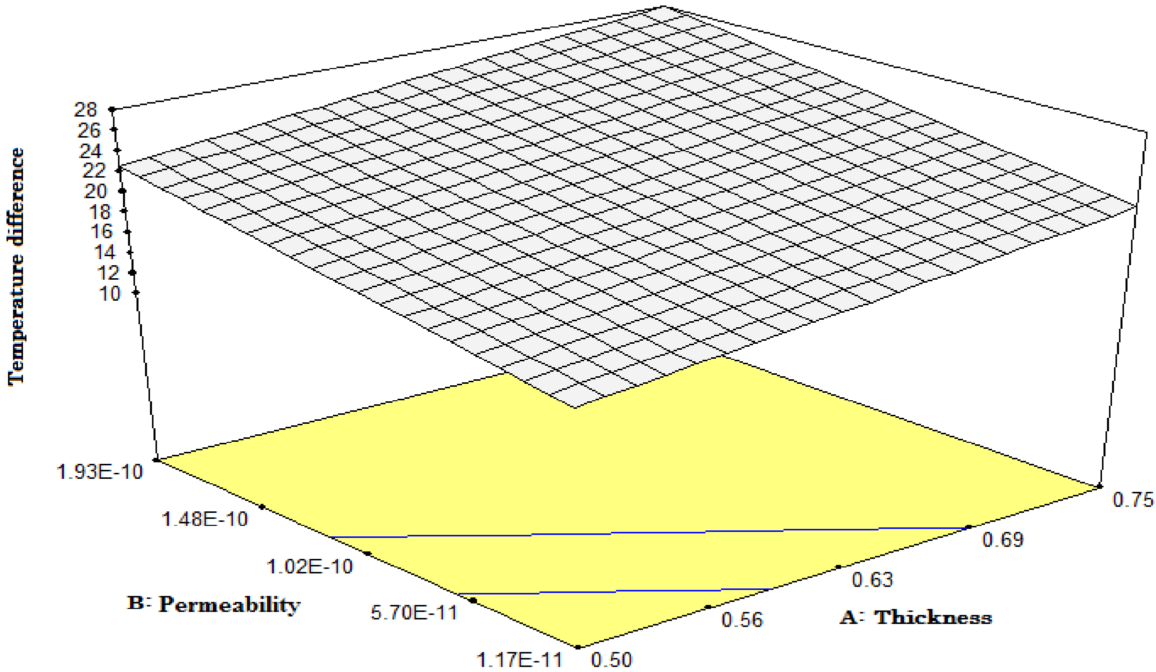
have a major effect on temperature difference and pressure drop. As shown in Figures 4 (a) and 4 (c) for both water and methanol, the decrease in permeability increases the effective thermal conductivity of liquid-wick, and hence the temperature difference decreases. Moreover, with the decrease in the wick thickness, the temperature difference decreases. Additionally, for both working fluids, water and methanol, the decrease in the wick permeability leads to a remarkable increase of the liquid pressure drop and the decrease in the wick thickness also leads to an increase in the liquid pressure drop, as shown in the Figures 4 (b) and 4 (d). The pressure drop resulting from the use of methanol is greater than the pressure drop resulting from the use of water, as the viscosity of methanol is greater than the viscosity of water.



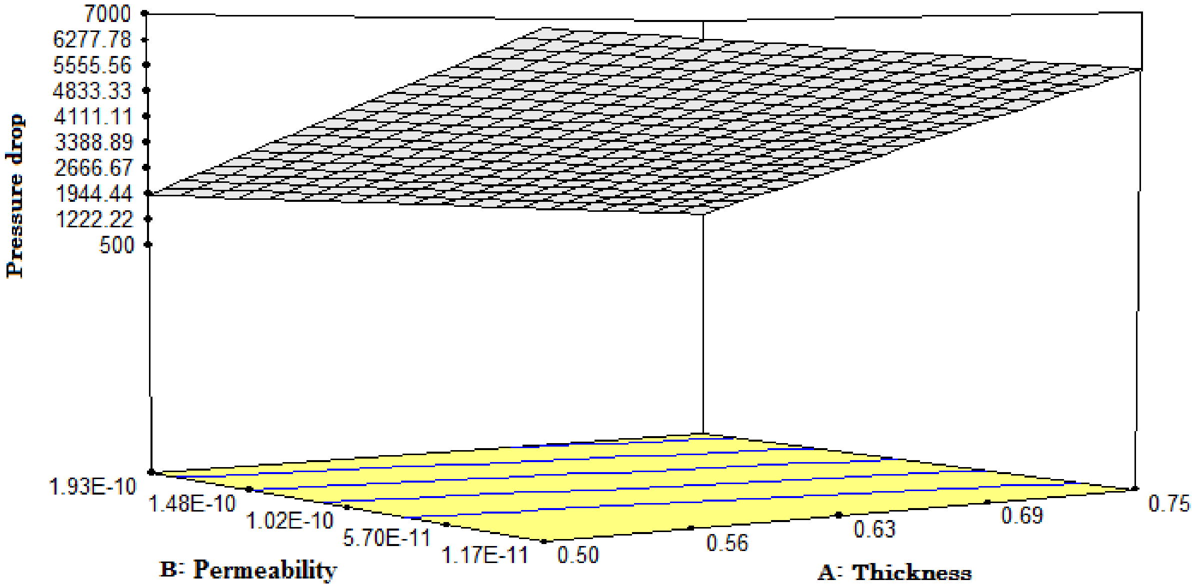
a) 3D surfce plots of temperature differernce (ΔT) as function of wick thickness and wick permeability when water is used as working fluid.



b) 3D surfce plots of pressure drop as function of wick thickness and wick permeability when water is used as working fluid.



c) 3D surfce plots of temperature differernce (ΔT) as function of wick thickness and wick permeability when methanol is used as working fluid.



d) 3D surfce plots of pressure drop as function of wick thickness and wick permeability when methanol is used as working fluid.

Figure 4. 3D surface for temperature difference (ΔT) and pressure drop (ΔP_l) as a function of wick thickness and wick permeability for the; (a) water- ΔT, (b) water- ΔP_l , (c) methanol- ΔT, (d) methanol- ΔP_l

4.3. Optimization Results

In numerical optimization using D-optimal Design software, the wick preamablity and wick thickness were goaled to be in range; the temperature differences and the pressure drop were aimed to be minimum. The optimization results yielded that a wick thickness of 0.52 mm and preamability of 1.39E-11 m^2 with water as working fluid could produce the minimum temperature difference of 9.56 °C and liquid pressure drop of 5730 Pa (less than about 833 Pa from the orginal pressure drop 6563 at the same heat input 35 W). These values commensurate with the experimental results of Elnaggar *et al.* [17]. Thus a model of good thermal performance of heat pipe with the proper pressure drop has been obtained which could increase the heat transport capability from 35 W to 43 W with about a 20% increase, where the values were confirmed by applying equation (2) in an analytical method.

The result of the optimization using D-optimal design software reveals that the performance of L-shape heat pipe in terms of heat transport capability is improved by 20%.

5. Conclusion

D-optimal designs software was performed to optimize the thickness and the permeability of wick structure with different working fluids of L-shape heat pipe for electronic devices cooling. The three significant parameters, wick thickness, wick permeability, and working fluids, are considered in this study with the objective of minimizing the temperature difference ΔT and liquid pressure drop ΔP_l to get the best performance of the heat pipe. The optimization results yielded that a wick thickness of 0.52 mm and preamability of 1.39E-11 m^2 with water as working fluid could produce the minimum temperature difference of 9.56 °C and liquid pressure drop of 5730 Pa which increased the heat transport capability from 35 W to 43 W.

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