Journal of Industrial Strategic Management, Year 2021, Volume 6 (Issue 2), Pages: 93-102

Journal of Industrial Strategic Management

Multi Objective Optimization of Heat Pipe Using Firefly Algorithm

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C H R O N I C L E

Article history
Received: 10/05/2021
Received in revised: 01/09/2021
Accepted: 11/09/2021

Keywords:
**heat pipe,*
**micro grooved*
**optimization*
**,firefly algorithm*

Abstract

In the present study, a firefly algorithm is used to achieve a multi objective optimization of heat pipe with axial “Ω” shaped micro grooves. The objective function of the optimization procedure is maximization of heat transport capability and minimization of the total thermal resistance. So the effects of geometrical dimensions and structural parameters on heat pipe performance have been considered as decision variables. Also heat transfer capability and total thermal resistance of heat pipe have been considered as objective function. The agreement between experimental data and calculated results confirms the accuracy of the proposed algorithm for micro groove heat pipe analysis .The effect of grooves number and vapor core diameter on heat transfer and total thermal resistance have been analyzed and it shows by increasing the number of grooves and core diameter, heat transfer capability and total thermal resistance increased. Heat transfer capability and total thermal resistance decreased by increasing width of slot. For equal in size width slot by increasing grooves diameter heat transfer and total thermal resistance respectively increased about 25% and 7%. Result shows working temperature significantly effects on the heat transfer capability and maximum heat transfer capacity occurred about 271 K.

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1. Introduction

Heat pipes are heat transfer devices which transfer heat from one point to another. Heat pipes have different types and one of them is a heat pipes with axial microgrooves. These axial microgrooves are in different shapes, such as triangular, rectangular, trapezoidal and ‘’Ω”-shaped . The heat pipe with axial ‘’Ω”-shaped micro grooves is shown in fig. 1. This kind of heat pipe is used in application when high thermal performance and excellent heat transfer capability requirements (Yong ping et al 2015). So heat transfer improvement is a key point on heat pipe performance (Zhang et al 2009). For this purpose, optimization method can be used. In this way the various parameters can be taken to improve heat transfer performance such as geometry, cost, mass and material therefore mathematical modeling for optimizing method seems necessary (Faghri et al 1995) presented an experiment on flat plate heat pipe and shown temperature distribution along wall surface is uniform and they found the main thermal resistance on evaporator section creates by porous wick (Wang and Vafai 2000) used analytically and experimentally data to find out the temperature field in flat plate heat pipes with micro-grooves. Also they introduced new mathematical model to calculate the vapor and liquid pressures and velocities.
This model used to optimize the heat pipe.
(Lefe`vre et al 2008) used Experimental data to validate the parameters effect such as saturation temperature and geometry on hydrodynamic and the maximum heat transfer capability of flat micro heat pipes.
Finally they introduced two correlations to determine thermal conductivity during condensation and evaporation (Revellin et al 2009). Focusing on a recuperated closed Brayton cycle (CBC), thermodynamic modeling of a CBC is proposed. Moreover, a thermal model is carried out to predict the overall properties of the cold side of the system (i.e., heat pipes and radiator) for different CBC conditions. Both models are coupled and their conjunct solution provides operational data for the design of the heat rejection system, such as the number of heat pipes (HP), total assembly mass, length, and second-law efficiency (Luis et al 2021) modelled triangular and drop-shape of a flat heat pipe. Studied on working fluid performance shows hydraulic behavior occurring at the end of the condenser on length of the liquid plug (Chauris et al 2013) presented mathematical model for thermal optimization of a miniature heat pipe with a grooved wick structure to maximize heat transfer and minimization of thermal resistance. They considered effects of contact angle; shear stress and amount of initial liquid charge and found by optimizing they can enhance heat transfer up to 48%. To verify the model used an experimental data (Kim et al 2003) the heat transfer model and energy consumption model of the integrated heat pipe cooling system was established to describe the relationship between operating parameters and energy efficiency. Based on genetic algorithm, energy efficiency optimization operation strategy was calculated at different load rates and outdoor ambient temperature. An experiment was carried out to verify the accuracy of the optimization algorithm (Zhiguang et al 2021) developed a mathematical model for thermal performance and studied the effects of parameters such as contact angle on the maximum heat transport rate of a flat micro heat pipe with a rectangular grooved wick structure. The effects of width and the height of the groove have been considered as decision variables in optimization procedure to maximize heat transfer. Data result validated by experimental data (Do et al 2008).
Developed a one-dimensional mathematical model under steady-state conditions to find out the geometric design

influence on the thermal performance of star-groove micro-heat pipes. They show by increasing the cross-sectional area heat transfer capability has increased (Hung and Seng 2011) presented experiment to detect the inner surface treatments influence on heat transfer of grooved heat pipes performance. Oxidation treatment on the inner surface can reduce the contact angle. So the heat transport capability has increased (Hu et al. 2013) worked on mathematical model to explore the characteristics solid wall and working fluid influence on thermal performance of micro heat pipes under steady-state conditions. The results indicate water is the best working fluid in a micro heat pipe (Chang and Hung 2014) presented mathematical model to increase capillary and heat transfer capability and reduced total thermal resistance of grooved copper heat pipe with use of gradient wettability surface. (Cheng et al 2017) Investigated on thermal performance of a bent copper-water heat pipe with grooved inner surface and studied on experimental data which shown the change of the inclination angle more influence on the heat flux and thermal performance of bent copper-water heat pipe. (Ghorbani et al 2013) Worked on model of inclined micro heat pipes with axial solid wall conduction to find out the effect of gravity on the thermal performance under steady-state conditions for optimally designed. It is found gravity can enhance heat transfer capability and working fluid circulation of micro heat pipes.

(Salehi et al 2020) Focused on simulation of a V-shaped micro heat pipe and developed a new method for calculating dry-out length and studied on designing and operating parameters effect on micro heat pipes performance. The results indicate heat pipe performance reduced by increasing in the viscosity, apex angle and length of heat pipe. (Momeni et al 2018) focused on effect of the GEO (Generalized extremal optimization) algorithm to design and optimization of a heat pipe in space application. (Mofrad et al 2020) used PSO (Particle Swarm Optimization) algorithm to optimize heat pipe. (Ghiasi et al 2021) developed a theoretical model and studied on parameters variations on the maximum heat transport capability in a heat pipe with axial ‘‘Ω” shaped grooves. (Deng et al. 2014) used experiments data from capillary rise in copper parallel micro V-grooves heat pipe using acetone and ethanol as a working fluid to compare the theoretical models data. A mixed integer linear program used by (Eshraghi et al 2019) for combined cooling and heating with heat storage.

In this study a mathematical model of heat pipe with axial ‘‘Ω” shaped micro grooves was considered and the firefly algorithm used to obtain an optimal design. The effect of geometrical dimensions and structural parameters influence on heat pipe performance considered as decision variables and heat transfer capability and total thermal resistance of heat pipe considered as objective function to optimize. The effects of the structural parameters for example number of grooves, vapor core diameter and wick thickness on objective function were considered for analyzing heat transfer capability and total thermal resistance.

2. Mathematical model

2.1. Heat transfer capability

In heat pipes with axial ‘‘Ω”-shaped micro grooves, the vapor flows in the vapor core at the center of the heat pipe and liquid flows in the capillary micro grooves, using Laplace–Young equation the capillary pressure can be calculated as

$$P_c = P_v - P_l = \sigma\left(\frac{1}{r_{c1}} + \frac{1}{r_{c2}}\right) \quad (1)$$

Where P_v and P_l are pressure of vapor and liquid respectively, and P_c is the capillary pressure. r_{c1} and r_{c2} are the radial and axial capillary radius of the meniscus. Since$r_{c2} \gg r_{c1}$, it is reasonable to suppose that $r_{c2} \rightarrow \infty$ and $r_{c1} \approx r_c(z)$. hence differential form of Eq. (1) is given by,

$$\frac{dP_v}{dz} - \frac{dP_l}{dz} = -\frac{\sigma}{r_c^2(z)} \frac{dr_c(z)}{dz} \quad (2)$$

Where $r_c$is capillary meniscus radius, σ is the surface tension coefficient. So heat transfer can be maximum if heat pipe operate at steady-state condition. At the evaporator section end cap (z = 0) the capillary radius can be represent as $r_{c,eva} = W/(2\cos\theta)$, while capillary radius at the condenser section end cap is $(z = L_e + L_a + L_c) r_{c,con} = r_v$, and $\theta$is the contact angle. The liquid and vapor pressure at the condenser section end cap can be considered as $P_v = P_{v0}$

$$P_l = P_{v0} - \frac{\sigma}{r_{c,con}} (z = L_e + L_a + L_c) \quad (3)$$

At the condenser section end cap P_{v0} is the vapor pressure. Therefore, the heat transfer capability Q can be calculated. The maximum allowable heat input rate during the start-up condition is.

$$Q_{max} = 0.4\Pi r_c^2 0.73 h_{fg} (P_v \rho_v)^{\frac{1}{2}} \quad (4)$$

where, $r_c$is the vapour channel radius, h_{fg} is the latent heat of vaporisation, P_v is the vapor pressure and ρ_v is the vapor density in the evaporator section.

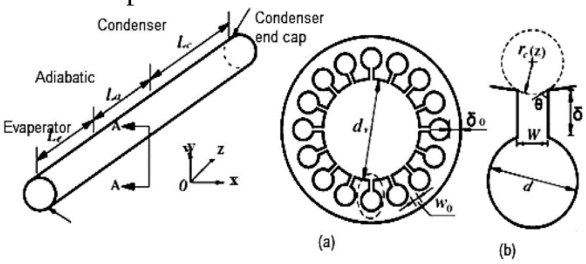

Fig. 1. Heat pipes with axial ‘‘Ω”-shaped micro grooves. (a) Cross section. (b) Schematic of grooves [2].

2.2. Total thermal resistance

The total thermal resistance is one of the main important factors in determination of the heat transfer performance of heat pipes. This parameter directly presents the degree of temperature uniformity. The thermal resistance of evaporator section, R_e, thermal resistance of condenser section, R_c, and thermal resistance due to the vapor flow, R_v are calculated from the following equations.

$$R_e = \frac{1}{N} \frac{(R_1 + R_2 + R_3)(R_4 + R_5)}{R_1 + R_2 + R_3 + 2(R_4 + R_5)} \quad 5)$$

$$R_c = \frac{1}{N} \frac{(R_6 + R_7 + R_8)(R_9 + R_{10})}{R_6 + R_7 + R_8 + 2(R_9 + R_{10})} \quad (6)$$

$$R_v = \frac{T_{work}(P_{v,e} - P_{v,c})}{\rho_v h_{fg} Q_{in}} \quad (7)$$

$$R_1 = \frac{\delta_0}{K_s W_f L_e} \quad (8)$$

$$R_2 = \frac{h_g}{K_{s,eq} W_f L_e} \quad (9)$$

$$R_3 = \frac{1}{\alpha_{film}(h_f - h_g) L_e} \quad (10)$$

$$R_4 = \frac{\delta_0}{K_s W L_e} \quad (11)$$

$$R_5 = \frac{h_g}{K_l W L_c} \quad (12)$$

$$R_6 = \frac{\bar{\delta}_{film}}{K_l W_f L_c} \quad (13)$$

$$R_7 = \frac{h_f}{K_{s,eq} W_f L_c} \quad (14)$$

$$R_8 = \frac{\delta_0}{K_s W_f L_c} \quad (15)$$

$$R_9 = \frac{h_g}{K_l W L_c} \quad (16)$$

$$R_{10} = \frac{\delta_0}{K_s W L_c} \quad (17)$$

where N is the groove number, ρ_v is the vapor density, $P_{v,e}$ and $P_{v,c}$ are the vapor pressure at the evaporator and condenser section respectively, T_{work} is the working temperature, Q_{in} is the heat load, h_{fg} is the latent heat, $K_l$and $K_s$are the conductivity of liquid and solid respectively, $K_{s,eq}$is the equivalent conductivity coefficient of groove fin, L_e and L_c are the length of evaporator and condenser respectively ,$\bar{\alpha} = \frac{K_l}{0.185 W_f}$ is the evaporating thin film heat transfer coefficient and $\bar{\delta}_{film}$ is the mean condensate liquid film thickness. The total thermal resistance is computed as:

$$R_{tot} = R_e + R_c + R_v \quad (18)$$

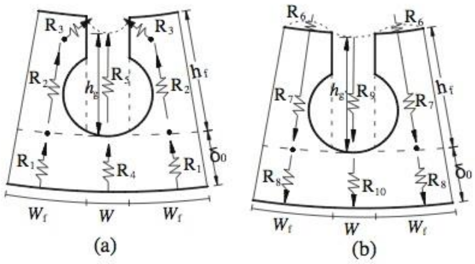

Fig. 2. Thermal resistance. (a) Evaporator section. (b) Condenser section [2].

2.3. Objective function

In this study the total thermal resistance and heat transfer capability of the heat pipe are selected as objective functions. The total thermal resistance should be minimized while heat transfer capability should be maximized. For determination objective function five parameters are selected as decision variables in the optimization process as fallows. The slot width W, wick diameter d, slot height δ, vapor core diameter d_v and groove number N. The objective function can expressed as .

$$\mathrm{Q} = f_1(\mathrm{W}, \mathrm{d}, d_v, \delta, N) \quad (19)$$

$$R_{tot} = f_2(\mathrm{W}, \mathrm{d}, d_v, \delta, N) \quad (20)$$

The boundary condition and constrain that used for optimizing objective function are given by

$$\frac{d_v}{2} + \delta + \frac{\sqrt{d^2 - W^2}}{4} + \frac{d}{2} + \delta_0 = \frac{d_0}{2} \quad (21)$$

$$N(w_0 + d) = 2\pi\left(\frac{d_v}{2} + \delta + \frac{\sqrt{d^2 - W^2}}{4}\right) \quad (22)$$

$$W \le d \quad (23)$$

N is integer (24)

$$w_0 \ge w^{/} \;,\; \delta_0 \ge \delta^{/} \;,\; W \ge s \;,\; \delta \ge s \;,\; d_v \ge s \quad (25)$$

$$w^{/} = 0.36\text{mm} \quad \delta^{/} = 0.4\text{mm} \quad s = 0.22\text{mm} \quad (26)$$

Geometrical constraints for radial and circumferential length are shown in Eqs. (21) and (22). Eqs. (23) is derived by the geometric shape of a ‘‘Ω”-shaped grooves, channel number must be an integer, minimal size limited by machining displayed by Eq. (25) where $w^{/}$, $\delta^{/}$ and s are the minimal sizes limited by machining.

3. Firefly algorithm

One of the important branches of artificial intelligence is swarm intelligence (SI), which has been developed during this decade. Difference swarm intelligence was created and developed by inspiration of the collective of social swarm of bees, ants, firefly and schools of fish. In other words, particle swarm optimization was based on the swarming behavior of insects, birds and animals.

Although several new algorithms have confirmed their ability in solving optimization problems, Firefly Algorithm (FA) is more efficient and reliable in solving global optimization problems. Firefly Algorithm (FA) is a kind of meta-heuristic algorithm, which was first developed by Xin-She Yang at Cambridge University. The heuristic word refers solution by trial and error. Exploration and exploitation are two major components on each meta-heuristic search process that must be a balance between them. The exploitation means use of existing information, so the exploitation can be express focusing and finding the search procedure within the proximity of the best solutions. The exploration means collection of new information, therefore the exploration can define as the process of discovering the various solutions within the search space.

Firefly algorithm uses a kind of randomization by searching for a set of solutions. This method used by the flashing lights of fireflies in nature. Firefly algorithm uses randomization in the search process to eschew the solution being trammeled into local optimal. The local search for finding the solution in local optimum, should improve a candidate solution until improvements are discovered.

Firefly attraction and attractiveness can change with distance. All Fireflies population automatically can be classified into different subgroups. Each group swarm around each local optimum mode, the best and efficient global solution can be discovered among these modes. For discovering the best location in the search space, firefly algorithm generates random initial population of possible candidate solutions. Whole of the solutions are considered in solution search space. For updating the knowledge of the firefly and its neighbors, every firefly in the population can travel in a multi-dimensional search space dynamically. The general process of the firefly algorithm is started by initialization of a swarm of fireflies for determination of flashing light intensity. The firefly algorithm has been inspired by behavior and the flashing patterns of fireflies. The three idealized main rules for the flashing characteristics are.

1. All fireflies are unisex and one of them can attract other fireflies without considering their sex.
2. The attractiveness is commensurate to firefly flashing brightness, so both of them decrease when the distance increases. If a firefly finds brighter flashing, it will move toward one, otherwise it will move randomly.
3. Objective function can express as the brightness of the firefly flashing light, which should be optimized.

After initializing, four main steps should be considered for optimizing problem as follows

- Firefly evaluation
- Attractiveness and light intensity
- Distance
- Movement

3.1. Firefly evaluation

Firefly flashing light intensity evaluation depends on the considered problem. For example, in the present study the maximum heat transfers capability and minimum total resistance are considered.

3.2. Attractiveness and light intensity

Firefly algorithm is based on formulation of the attractiveness and the variation of the light intensity. The attractiveness is commensurate to the light intensity seen by neighbor fireflies and the attractiveness β of a firefly can be present as

$$\beta = \beta_0 e^{-\gamma r^2} \qquad (27)$$

In eq. (27), β_0 is the initial attractiveness at *r* = 0 and the distance between each pair of fireflies is r. The light intensity can be estimated using the following equation

$$I(r) = I_0 e^{-\gamma r^2} \qquad (28)$$

Where, *I(r)* is the light intensity at a distance r, γ is a fixed light absorption coefficient and I_0 is the intensity at the source. The attractiveness is a comparative measure of the light diagnosed by other fireflies while the intensity is explained as a complete measure of light sent out by the firefly.

3.3. Distance

The distance between any two fireflies can be defined as

$$r_{mn} = ||x_m - x_n|| = \sqrt{\sum_{k=1}^{d} (x_{m,k} - x_{n,k})^2} \qquad (29)$$

Where, r_{mn} is the Cartesian distance between any two fireflies m and n at x_m andx_n. Also $x_{m,k}$ is the ‘k'th component of the spatial coordinate x_m of the ‘m'th firefly and the number of dimensions mentioned as d.

3.4. Movement

Each firefly tends to another attractive or brighter firefly. Movement for the firefly algorithm can be formulated as

$$x_m = x_m + \beta_0 e^{-\gamma r_{mn}^2} (x_n - x_m) + \alpha\varepsilon \qquad (30)$$

As previously mentioned, the term $\beta_0 e^{-\gamma r_{mn}^2} (x_n - x_m)$ is expressed as the effect of attractiveness. Also the randomization term is shown with $\alpha\varepsilon$ in which α is the randomization parameter and $\varepsilon \in [0,1]$ term is vector of random numbers.

Modification of the flashing light absorption is an important factor for convergence of the firefly algorithm. In this process the initial value of the flashing light absorption parameter is specified a constant value and according to the optimization performance the initial value is modified. The firefly algorithm optimization procedure continues until the end of generation. At first one of the generated fireflies is assumed as the brightest in populations then the other fireflies move towards the brightest firefly. According to this performance, fireflies are ranked during optimization procedure. The distance and attractiveness of each firefly from brighter one is computed and it influences on the procedure of motion for each firefly differently.

4.2. Experimental validation

Heat pipe geometry data, which used in experiment tabulated on table 1 the mathematical model validate by experimental data, which on figure 4.

Measurement and calculation data shown maximum heat transport capability reduction caused by increment of working fluid temperature and difference between measurement and calculation data error reduced on lower temperature. Comparison between experimental data and generated data by firefly algorithm shown on figure 4. The algorithm calculation data gives 17.8%, 15.7% and 6.76% error in compare to measurement data respectively at temperature’s 319.3, 311.1 and 304.5 (k).

Table 1. Heat pipe geometry data in mm.

W	d_v	d	δ	L_e	L_a	L_c
0.46	6.41	1.4	0.67	700	560	590

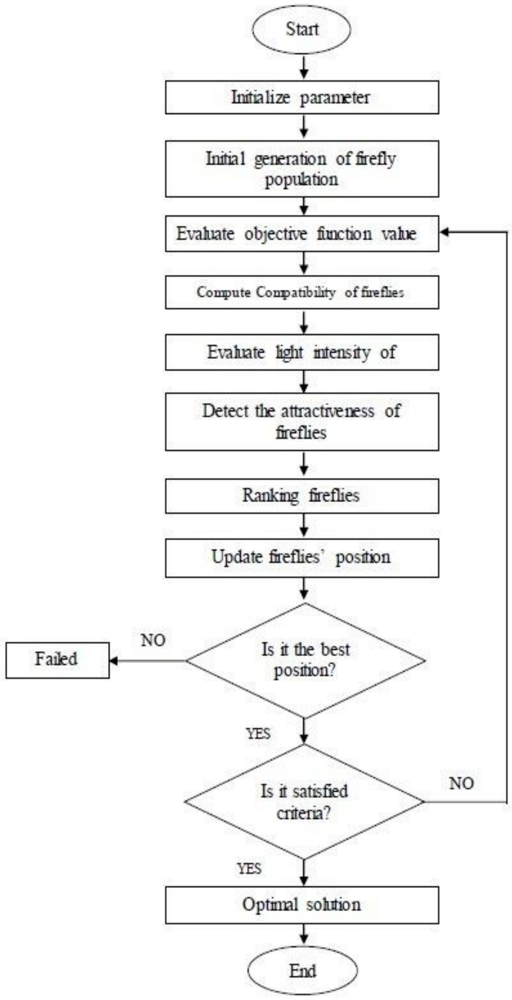

Fig 3. Flowchart of optimization problem

4. Result and optimization problem

A firefly algorithm used to solve optimization problem of heat pipe with axial ‘’Ω” shaped micro grooves with the conditions mentioned in table1. As previously noted, firefly algorithm belongs to a metaheuristic-based optimization which randomly determined.

In metaheuristic-based optimization algorithm it is required to have different optimization runs to determine the mean value of the objective function.

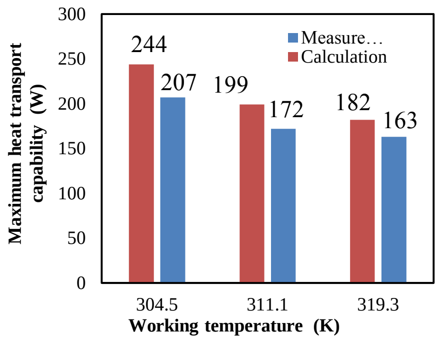

Fig 4. Comparison between experimental data and generated data by firefly algorithm

In this study 45 fireflies was considered as population size. The global optimum function evaluations, 4000 has been determined after about 60 optimization iterations. Fig. 5 and 6 represent the convergence of maximum heat input rate and total thermal resistance.

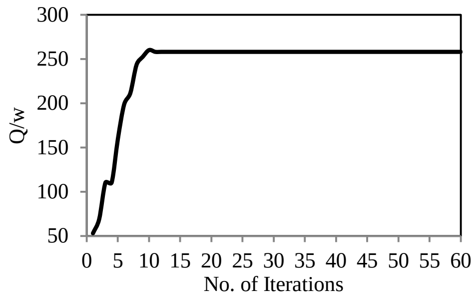

Fig 5. Convergence of firefly algorithm for maximum heat transfer

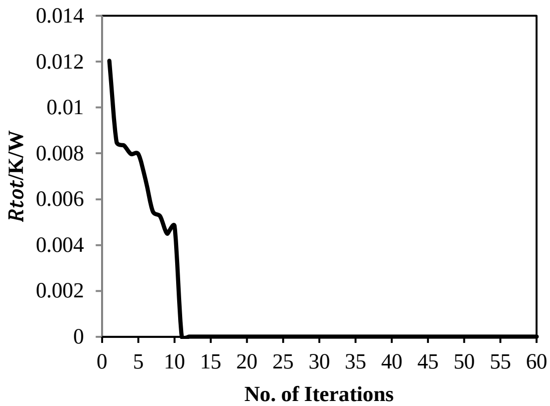

Fig 6. Convergence of firefly algorithm for total thermal resistance

The effect of number of grooves on heat transport capability and total thermal resistance as presented in figure 7 and 8. By increasing number of grooves heat transfer capability and total thermal resistance increased. By increasing vapor core diameter, heat transport capability increase and total thermal resistance decrease.

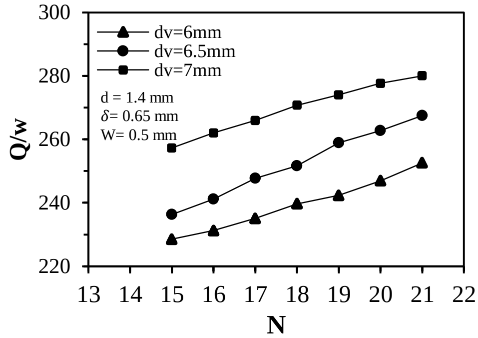

Fig 7. Effects of number of grooves and vapor core diameter on heat transfer

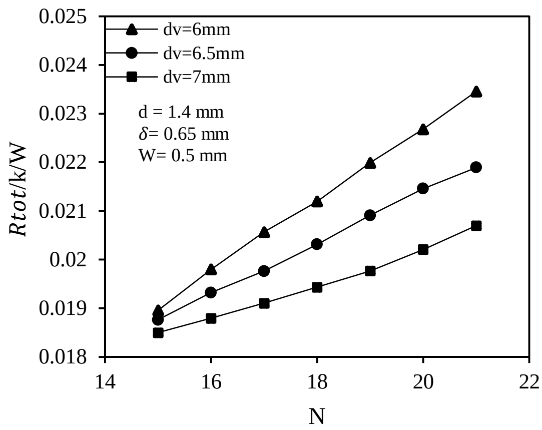

Fig 8. Effects of number of grooves and vapor core diameter on total thermal resistance

As it shown in fig. 9 heat transfer capability and total thermal resistance by increasing width of slot, decreased. For equal in size width slot when grooves diameter is larger, heat transfer capability and total thermal resistance increased had fewer amounts (fig 10, 11).

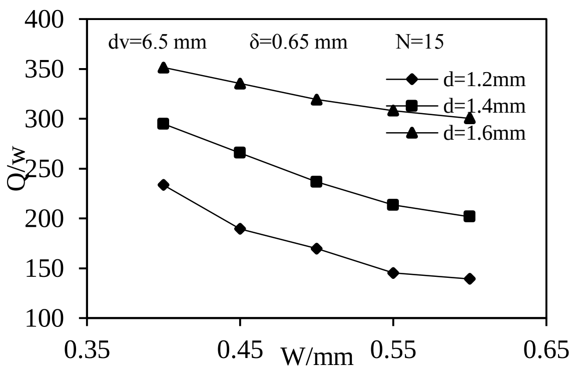

Fig 9. Effects of width of slot and grooves diameter on heat transfer.

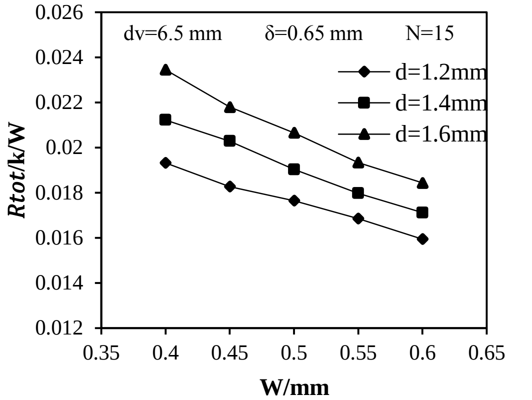

Fig 10. Effects of width of slot and grooves diameter on total thermal resistance.

Figures 12 and 13 show the maximum heat transfer capacity and variation of total thermal resistance at different working temperature for the heat pipe. Working temperature significantly effects on the rate of maximum heat transfer. The maximum heat transfer capacity occurred about 271 K. But working temperature has very light effect on total thermal resistance.

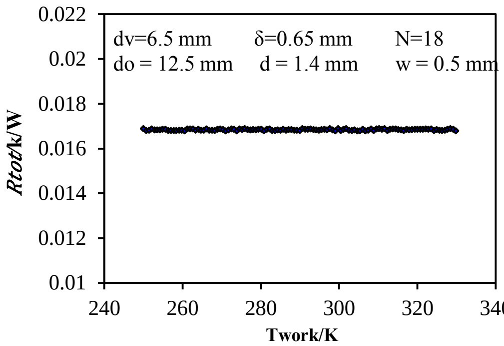

Fig 11. Variation of total thermal resistance at different working temperature

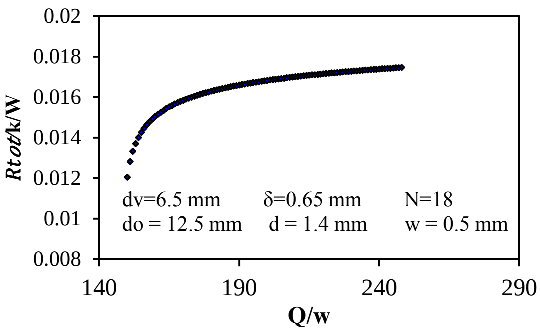

Fig 12. Total thermal resistance at different heat load

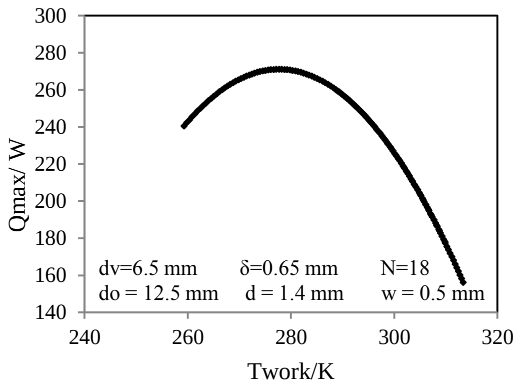

Fig 13. Maximum heat transfer capacity at various working temperatures.

5. Conclusions

In this study a mathematical model of heat pipe with axial ''Ω" shaped micro grooves was considered and the firefly algorithm used to obtain an optimal design. The objective function of the optimization procedure are maximization of heat transport capability and minimization of the total thermal resistance. The effects of the structural parameters on objective function, were considered for analyzing and it shows larger number of grooves, larger vapor core diameter and wick diameter and smaller wick slot width will increase the heat transfer capability But the total thermal resistance will increase. Calculation data shown when temperature of working fluid increased maximum heat transport capability decreased. Finally, comparison between mathematical and experimental data error respectively shows 17.8%, 15.7% and 6.76% which seems reasonable difference so experimental data can verified the mathematical model.

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