A novel flat heat pipe and its thermal performance analysis

Xiaoli Ma* **and S.B. Riffat**

Institute of Sustainable Energy Technology, Department of the Built Environment, University of Nottingham, Nottingham NG7 2RD, UK

Abstract

The paper presents a novel flat heat pipe that has the characteristics of easy to construct, can withstand a higher pressure when vacuumed and can be constructed into various scales. The thermal performance of the novel flat heat pipe with or without the wick was analysed using an analytical model. The analysis related to the relations of the maximum heat transport capacity with liquid fill level, working temperature and heat pipe geometry dimension for different working fluids.

Keywords: novel flat heat pipe; heat transport capacity; evaporator; condenser; wick

*Corresponding author: x.ma@nottingham.ac.uk

Received 18 February 2010; accepted 22 March 2010

1 INTRODUCTION

A flat heat pipe has an advantage over other heat pipes, in that it can be thermally connected to the parts to be cooled without difficulty due to its flat shape. A typical example is to conduct heat from or to the thermoelectric refrigeration devices. In order to have a good thermal contact with the thermoelectric device, the flat heat pipe should have a higher surface flatness. Currently, most applications of the flat heat pipe are in the area of cooling electric devices [1–4]. These flat heat pipes are usually miniature or micro flat heat pipes. The capillary force and the vacuum are the major difficulties in development of the flat heat pipe compared with the conventional circular heat pipe. Also, the flat heat pipes usually have more complicated manufacturing process to form the structural support and wick structure. For example, a sealed-plate heat pipe which has multiple independent through holes that containing wire mesh. The wire or wire mesh is disposed in at least one of the rectangular through holes such that a narrow space is formed between an inner wall of the partition wall forming through the hole and a side portion of the straight wire and wire mesh so as to cause sufficient capillary action (Figure 1a) [5]. A thin-sheet heat pipe comprises a hermetically sealed container, at least one spacer which is movably housed in the container, exerts a capillary force and has fluid path (Figure 1b) [6]. A flat-plate heat pipe has a shallow cavity base, a cover plate and a lanced-offset fin, which contains the porous metal wick material sandwiched in the space between. The fin is braced to the base and the cover plate to provide structural support and is also coated with the wick material (Figure 1c) [6].

As well known, the conventional circular heat pipe can withstand higher pressure due to its shape when vacuumed and easy to fit the wick by using metal mesh that can contact tightly with the internal surface of the circular tube by its tensile force. If the cross-sectional diameters or equivalent diameters are larger than 2 mm, the channel geometry can be circular or rectangular. The inner surface of these heat pipes may be fitted with wicks, which are used to produce capillary force to aid the operation of the heat pipes [7]. In this paper, a novel flat pipe which is derived based on the concept of the conventional circular heat pipe is presented and its thermal performance was analysed. The scale of the novel flat heat pipe can be varied to suit for applications in the areas of electronic equipment, solar energy systems, thermoelectric refrigeration systems, air-conditioning systems and industry to dissipate heat, in the cases of the flat heat pipes are needed.

2 NOVEL FLAT HEAT PIPE

The novel flat heat pipe is shown in Figure 2. The evaporator is a flat panel with circular holes inside the panel (Figure 2b). This structure can withstand a higher pressure when vacuumed and therefore keeps the surface of the panel flat, which is key point of the flat heat pipe. The holes connect each other at the bottom of the evaporator to keep the working fluid inside the flat heat pipe at the same level. As shown in Figure 2b, the condenser is consisted of pipes that connected with headers. The number of the pipes is equal to the number of the holes in the evaporator and the diameter of each pipe is equal to that of

International Journal of Low-Carbon Technologies 2010, 5, 111–117

doi:10.1093/ijlct/ctq014 Advance Access Publication 20 April 2010

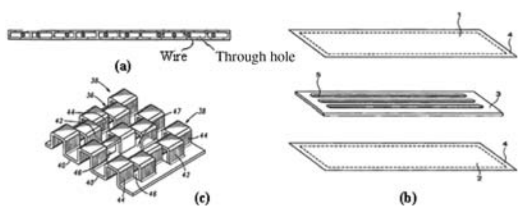

Figure 1. *Different flat heat pipe styles.*

the hole in the evaporator, i.e. the pipes on the condenser can be looked as an extension of the holes in the evaporator. The condenser pipes can be finned to distribute heat effectively. The evaporator and the condenser are connected by the adiabatic section. The adiabatic section is a circular tube, which cross-sectional area is equal to the total cross-sectional area of holes in the evaporator (or pipes in the condenser). The adiabatic section connects directly with the header of the evaporator (which is also tubes having the cross-sectional area equal to the cross-sectional area of the adiabatic section) and one of the header of the condenser. The angle between the evaporator/condenser and the adiabatic section can be made various ($90^\circ - 180^\circ$) easily to meet the special application. Figure 3a shows a configuration of the angle to be 180° and Figure 3b shows a configuration of the angle between 90° and 180°. The adiabatic section can be replaced with a flexible pipe that gives more flexible arrangement of the condenser location (Figure 3c). The internal surface of the hole in the evaporator can be fitted with a capillary wick (metal mesh) to drive the liquid condensate from the bottom and distribute it to the internal surface of each hole to form liquid film. This flat heat pipe can also work without the wick in the holes in the evaporator; in this case, the liquid fill level should be close to 100% evaporator length, otherwise, the internal surface of the holes in the evaporator may be partly dry due to the condensate return from the adiabatic section by gravity and may not form the liquid film evenly on each hole surface, which will affect the heat pipe efficiency. The novel flat heat pipe can operate as a thermal diode to transfer and dissipate the heat from the component to be cooled. As the whole flat heat pipe consists of circular pipes and holes, it can withstand higher pressure without the need of any support like other flat heat pipes.

The scale of this novel flat heat pipe is mainly determined by the diameter and number of the holes in the evaporator. The diameter of the holes should be larger than 2 mm as mentioned in Section 1. Thermal performance analysis has been carried out in order for optimum design of the novel flat heat pipe.

3 ANALYTICAL MODEL SET-UP: LIMITS OF HEAT TRANSPORT CAPACITY

The formulae for limits of heat transport capacity for conventional heat pipes with or without the wick were developed. On the basis of these formulae, the calculation of maximum heat transport capacity of the novel flat heat pipe was also presented.

Consider each channel (a hole in the evaporator and a pipe in the condenser) in the novel flat heat pipe as a single conventional heat pipe. All the single pipes have the same adiabatic section. The cross-sectional area of the adiabatic section is equal to the total cross-sectional area of all the pipes. The novel flat heat pipe can then be taken as numerous single heat pipes parallel in width. First, we will consider a single pipe as a

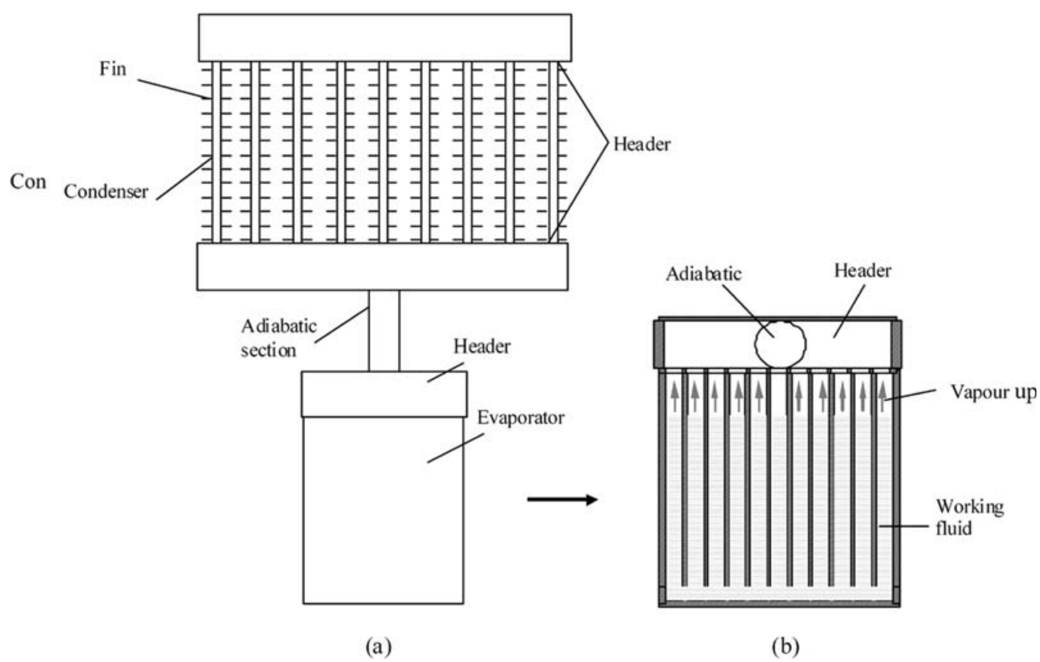

Figure 2. *Novel flat heat pipe. (a) Configuration of the novel heat pipe. (b) Inside view of the evaporator.*

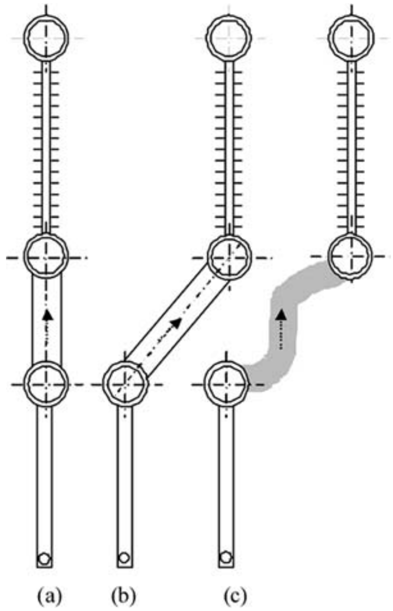

Figure 3. *Different adiabatic sections (a) angle to be 180° (b) angle between 90°–180° (c) flexible adiabatic section.*

simulation object and determine its optimum sizes and working conditions. This concept can then be developed to simulate the whole thermal diode.

Owing to all, the single holes in the evaporator connecting each other, a natural circulation flow is created in the evaporator of the novel flat heat pipe, gravity therefore does not play a role in promoting fluid flow in the evaporator. This will be considered in the calculation of the capillary limit.

For any heat pipe, the maximum heat transport capacity is governed by six limits [8]; namely, the sonic limit, the entrainment limit, viscous limit, boiling limit, capillary limits and liquid fill limits. Using the techniques presented in Dunn and Reay [8] and Babin and Peterson [9], the above five limits may be expressed as:

Sonic limit

$$q_{\mathrm{s,m}} = k_{\mathrm{s}} A_{\mathrm{v}} \rho_{\mathrm{v}} h_{\mathrm{fg}} \left(\frac{\gamma R_{\mathrm{vc}} T_{\mathrm{v}}}{2(\gamma+1)} \right)^{1/2} \tag{1}$$

where k_{s} is the shape factor of the heat pipe channel geometry (for circle channel, $k_{\mathrm{s}} = 1$).

Entrainment limit

$$q_{\mathrm{e,m}} = k_{\mathrm{s}} A_{\mathrm{v}} h_{\mathrm{fg}} \left(\frac{\sigma \rho_{\mathrm{v}}}{2 r_{\mathrm{h,w}}} \right)^{1/2} \tag{2}$$

Boiling limit

$$q_{\mathrm{b,m}} = \frac{2\pi l_{\mathrm{eff}} k_{\mathrm{eff}} T_{\mathrm{v}}}{h_{\mathrm{fg}} \rho_{\mathrm{v}} \ln(r_{\mathrm{i}}/r_{\mathrm{v}})} \left(\frac{2\sigma}{r_{\mathrm{n}}} - \Delta p_{\mathrm{c,m}} \right) k_{\mathrm{s}} \tag{3}$$

Viscous limit

$$q_{\mathrm{v,m}} = \frac{k_{\mathrm{s}} r_{\mathrm{v}}^2 h_{\mathrm{fg}} \rho_{\mathrm{v}} p_{\mathrm{v}} A_{\mathrm{v}}}{16 \mu_{\mathrm{v}} l_{\mathrm{eff}}} \tag{4}$$

Capillary limit

$$\Delta p_{\mathrm{cl}} \geq \Delta p_{\mathrm{rg}} + \Delta p_{\mathrm{ag}} + \Delta p_{\mathrm{l}} + \Delta p_{\mathrm{v}} \tag{5}$$

Owing to the influence of gravity on the heat pipes investigated, the heat transport capacity is also governed by the filled liquid mass. Zhuang [10] expressed this parameter as follows:

$$G_{\mathrm{f}} = (0.8 l_{\mathrm{c}} + 0.8 l_{\mathrm{e}} + l_{\mathrm{a}}) \left(\frac{3\mu_1 \rho_1 \pi^2 d_i^2}{k_1 h_{\mathrm{fg}} g} \right)^{1/3} q_{\mathrm{c}}^{1/3} \tag{6}$$

For the heat pipe without the wick, there are no capillary pressure differences along the pipe length, i.e. $\Delta p_{\mathrm{cl}} = 0$. In addition, the entrainment limit may be expressed in a different way, as shown below [10]

$$q_{\mathrm{e,m}} = k_{\mathrm{s}} f_1(\phi) C_{\mathrm{w}}^2 \frac{\pi d_i^{2.5}}{4} \frac{h_{\mathrm{fg}} \sqrt{g \rho_{\mathrm{v}} (\rho_l - \rho_{\mathrm{v}})}}{[1 + (\rho_{\mathrm{v}}/\rho_{\mathrm{l}})^{0.25}]^2} \tag{7}$$

$C_{\mathrm{w}} = 0.725$

$$f_1(\phi) = \left(\frac{\phi}{180} + \sqrt{\sin 2\phi} \right)^{0.65} \tag{8}$$

For the novel flat heat pipe with the wick, Δp_{cl} is to drive the liquid from the bottom of the evaporator to the whole internal surface of the evaporator. Owing to the single hole connecting each other to create a natural circulation flow in the evaporator, gravity does not play a role in promoting fluid flow in the evaporator. This case is similar to the wicked conventional normal pipes located horizontally; the net capillary pressure difference Δp_{cl} is expressed as:

$$\Delta p_{\mathrm{cl}} = \frac{2\sigma}{r_{\mathrm{ce}}} \tag{9}$$

The capillary radius of mesh as wick is expressed as:

$$r_{\mathrm{ce}} = \frac{w + d}{2} \tag{10}$$

where w is the distance between the adjacent wires and d the diameter of the mesh wire.

The radial and axial hydrostatic pressure drops Δp_{rg} and Δp_{ag} are the result of the gravitational forces and may be expressed as:

$$\Delta p_{\mathrm{rg}} = -\rho_{\mathrm{l}} g d_{\mathrm{v}} \cos \phi \tag{11}$$

$$\Delta p_{\mathrm{ag}} = -\rho_{\mathrm{l}} g l_{\mathrm{p}} \sin \phi \tag{12}$$

where l_{p} is the length of the liquid column in the heat pipe;

$$l_{\mathrm{p}} = l_{\mathrm{c}} + l_{\mathrm{a}} \sin \psi \tag{13}$$

where ψ is the angle between the adiabatic section and the horizontal surface. As a natural circulation flow is created in the evaporator, gravity forces do not play a role on hydrostatic pressure drops in the evaporator, l_{p} does not include the length of the liquid column in the evaporator.

$$\Delta p_{\mathrm{l}} = -\left(\frac{\mu_{\mathrm{l}}}{KA_{\mathrm{l}}h_{\mathrm{fg}}\rho_{\mathrm{l}}}\right)l_{\mathrm{eff}}q_{\mathrm{c}} \tag{14}$$

For the pipe with the wick

$$K = \frac{r_{\mathrm{hl}}^2}{8} \tag{15}$$

For the pipe without the wick

$$K = 1 \tag{16}$$

$$l_{\mathrm{eff}} = 0.5l_{\mathrm{e}} + l_{\mathrm{a}} + 0.5l_{\mathrm{c}} \tag{17}$$

$$\Delta p_{\mathrm{v}} = \left(\frac{C(f_{\mathrm{v}}\mathrm{Re}_{\mathrm{v}})\mu_{\mathrm{v}}}{2(r_{\mathrm{hv}})^2A_{\mathrm{v}}\rho_{\mathrm{v}}h_{\mathrm{fg}}}\right)l_{\mathrm{eff}}q_{\mathrm{c}} \tag{18}$$

$$\mathrm{Re}_{\mathrm{v}} = \frac{2(r_{\mathrm{hv}})q_{\mathrm{c}}}{A_{\mathrm{v}}\mu_{\mathrm{v}}h_{\mathrm{fg}}} \tag{19}$$

$$M_{\mathrm{v}} = \frac{q_{\mathrm{c}}}{A_{\mathrm{v}}\rho_{\mathrm{v}}h_{\mathrm{fg}}(R_{\mathrm{vc}}T_{\mathrm{v}}\gamma)^{0.5}} \tag{20}$$

Kraus and Bar-Cohen [11] gave the expressions for f_{v} and C, for different sets of conditions, as follows:

$$\mathrm{Re}_{\mathrm{v}} \le 2300, \quad M_{\mathrm{v}} \le 0.2, \quad f_{\mathrm{v}}\mathrm{Re}_{\mathrm{v}} = 16, \quad \mathrm{C} = 1.00 \tag{21}$$

$$\mathrm{Re}_{\mathrm{v}} \le 2300, \quad M_{\mathrm{v}} \succ 0.2, \quad f_{\mathrm{v}}\mathrm{Re}_{\mathrm{v}} = 16, \quad C = C_1 = \left(1 + \left(\frac{\gamma-1}{2}\right)M_{\mathrm{v}}^2\right)^{0.5} \tag{22}$$

$$\mathrm{Re}_{\mathrm{v}} > 2300, \quad M_{\mathrm{v}} \le 0.2, \quad f_{\mathrm{v}}\mathrm{Re}_{\mathrm{v}} = 0.038, \quad C = C_2 = \left(\frac{2\gamma_{\mathrm{hv}}q_{\mathrm{c}}}{A_{\mathrm{v}}h_{\mathrm{fg}}\mu_{\mathrm{v}}}\right)^{0.75} \tag{23}$$

$$\mathrm{Re}_{\mathrm{v}} > 2300, \quad M_{\mathrm{v}} > 0.2, \quad f_{\mathrm{v}}\mathrm{Re}_{\mathrm{v}} = 0.038, \quad C = C_1C_2 \tag{24}$$

4 MODELLING AND DISCUSSIONS

A computer model was developed based on the mathematical description above and used to analyse the heat transfer of the novel flat heat pipe for the purpose of optimum designing the novel flat heat pipe. The investigation related to the relations of the maximum heat transport capacity with liquid fill level, working temperature and heat pipe geometry dimension. Both the novel flat heat pipe with and without the wick (mentioned in Section 2) were investigated. For the novel flat heat pipe with the wick, three layers of woven wire mesh (mesh count: 200) wick were assumed. The working fluids, *n*-pentane (working temperature range: −20 to 120°C) and HFE-7100 (working temperature range: −20 to 70°C) that have larger working temperature range, are used as working fluids in the modelling. For analysis of the relation between the maximum heat transport capacity and liquid fill level, temperature and cross-sectional diameter of the channel, the invariable parameters in the modelling are assumed, i.e. for both novel flat heat pipe with and without the wick, the lengths of the evaporator and condenser are 0.32 m, respectively, the lengths of the adiabatic section are 0.15 m. The angle between the evaporator/condenser and the adiabatic section is 120°. (These assumptions are based on the testing condition of the thermal diode operation in an experimental rig of a thermoelectric heat pump in the department.) The maximum heat transport capacities presented in the modelling results are for single channel. For the whole flat heat pipe, the maximum heat transport capacity is the maximum heat transport capacity for single channel multiplied by the number of the channels. The modelling results and discussions are discussed later.

4.1 Relation between maximum heat transport capacity and working temperature

Figure 4 shows the relations between maximum heat transport capacity and working temperature for the novel flat heat pipe with and without the wick. These results were obtained by further assuming the cross-sectional diameter to be 0.01 m and the liquid fill level to be 0.08 m.

The simulation results indicates that for the same values of the working temperature, the maximum heat transport capacities of the thermal diodes without the wick (dominated by entrainment limits) are much greater than those with the wick (dominated by capillary limits), and increase obviously with the working temperature. For the maximum heat transport capacities, *n*-pentane is superior to HFE-7100.

4.2 Relation between maximum heat transport capacity and liquid fill level

Figure 5 shows the relations between maximum heat transport capacity and liquid fill level for the novel flat heat pipe with and without the wick. The results were obtained by further assuming the cross-sectional diameter to be 0.01 m and the working temperature to be 45°C.

The simulation results indicate that the maximum heat transport capacities of the thermal diode with the wick (dominated by capillary limits) increase with liquid fill level. When the liquid fill level is >0.22 m, the increase is significant. However, to use the wick in the novel flat heat pipe is intending not to use higher liquid fill level, the role of the wick is to distribute liquid from the bottom of the evaporator to the whole internal surface of the evaporator. Normally, a liquid fill level of one-third to one-fourth of the evaporator length is suggested in

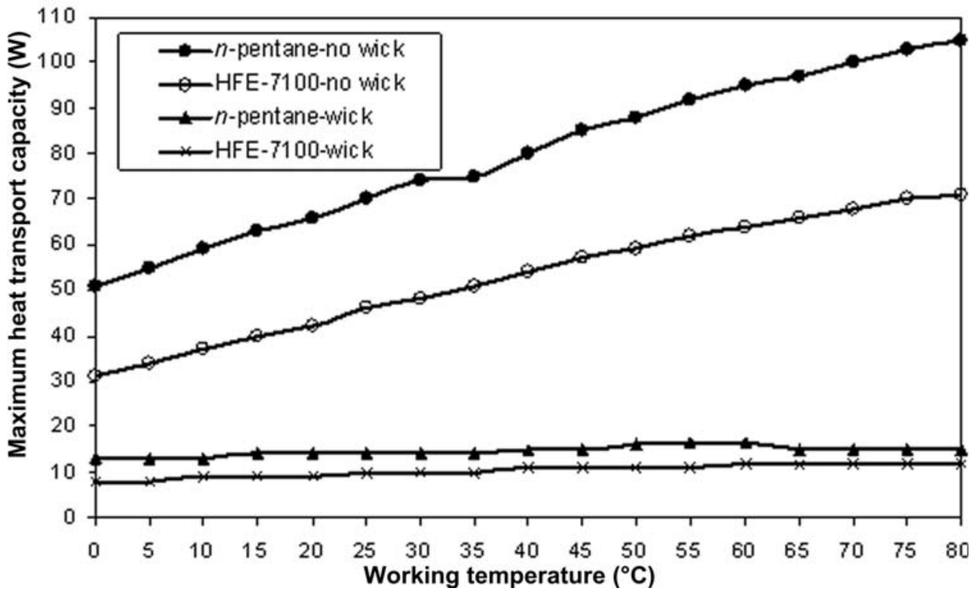

Figure 4. *Relation between heat transport capacity and working temperature.*

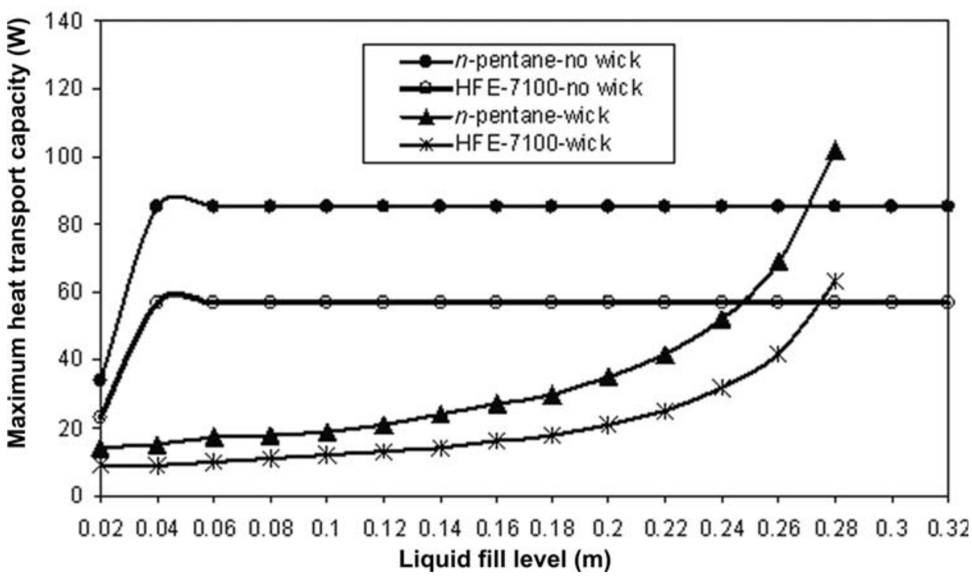

Figure 5. *Relation between heat transport capacity and liquid fill level.*

a heat pipe [8], in which cases, the maximum heat transport capacities of the thermal diode with the wick are only 18–19 W for *n*-pentane pipe, 11–12 W for HFE-7100 pipe.

The maximum heat transport capacities of the thermal diodes without the wick remain constant (85 W for *n*-pentane pipe and 57 W for HFE-7100 pipe) if the liquid fill level is >0.04 and are much more than that with the wick. When the liquid fill level is >0.04 m, for this modelling condition, the maximum heat transport capacities are dominated by the entrainment limit. When the liquid fill level is <0.04 m, the maximum heat transport capacities are dominated by dry-out limit, which increases with the liquid fill level. As mentioned in Section 2, for the novel flat heat pipe without the wick, the internal surface of the holes in the evaporator may be partly dry due to the condensate return from the adiabatic section by gravity and may not form the liquid film evenly on each hole's surface, which will affect the heat pipe efficiency. Therefore, the fill level is suggested to be 90–100% evaporator length, in case dry internal surface of the evaporator happens.

4.3 Relation between maximum heat transport capacity and cross-sectional diameter

Figure 6 shows the relations between the maximum heat transport capacity and cross-sectional diameter for the thermal

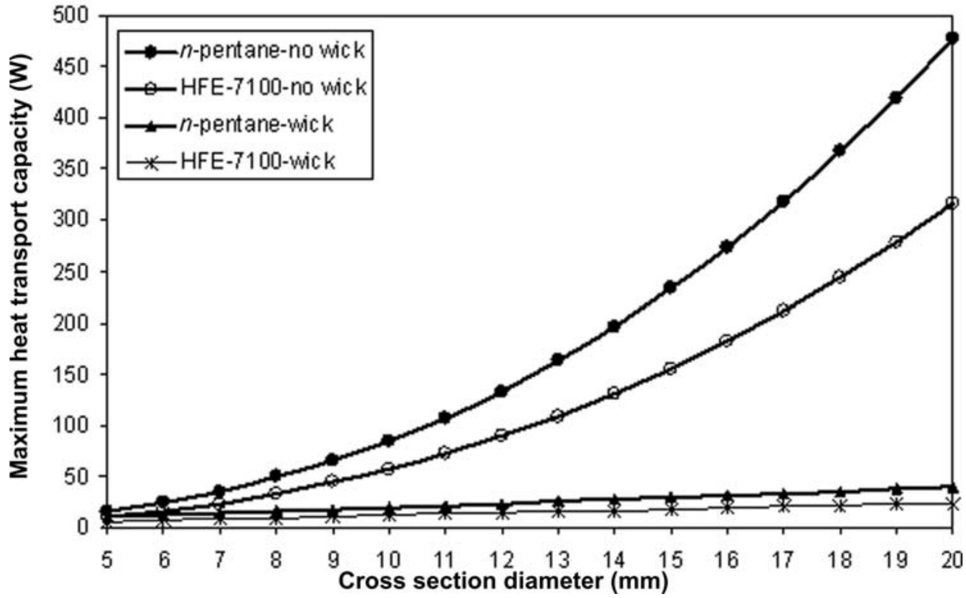

Figure 6. *Relation between heat transport capacity and cross-sectional diameter.*

diodes with and without the wick. The results were obtained by further assuming the working temperature to be 45°C and liquid fill level to be 0.1 m.

The heat transport capacities of the thermal diodes with and without the wick increase obviously with the increase in the cross-sectional diameters.

For the same values of cross-sectional diameter, the heat transport capacities of the novel flat heat pipe without the wick (dominated by the entrainment limit) are much greater than those of the pipe with the wick (dominated by the capillary limit).

4.4 Further analysis

The maximum heat transport capacities of the thermal diodes without the wick, dominated by the entrainment limit, are much greater than those of with the wick under the various working temperatures, liquid fill levels and cross-sectional diameters, while *n*-pentane and HFE-7100 are used as working fluids.

The maximum heat transport capacities of the thermal diode with the wick, dominated by the capillary limit, are much less because viscous pressure drop Δp_l occurring in the liquid phase is greater. The reason for causing greater viscous pressure drop is smaller coefficient for liquid phase resistance calculation and less latent heat of vaporization of *n*-pentane and HFE-7100.

5 CONCLUSIONS

The novel flat heat pipe consists of circular pipes and holes; it can therefore withstand higher pressure without the need of any support like other flat heat pipes. The novel flat heat pipe is easy to construct and form the wick structure, and can be constructed in various scales.

The computer simulation of the novel flat heat pipe found the following.

- The maximum heat transport capacities of the novel flat heat pipe without the wick, dominated by the entrainment limit, are much greater than that of with the wick under the various working temperatures, liquid fill levels and cross-sectional diameters, while *n*-pentane and HFE-7100 are used as working fluids.
- The maximum heat transport capacities of the novel flat heat pipe with the wick, dominated by the capillary limit, are much less because viscous pressure drop occurring in the liquid phase is greater. The reason that cause greater viscous pressure drop is smaller coefficient for liquid phase resistance calculation and less latent heat of vaporization of *n*-pentane and HFE-7100.
- The maximum heat transport capacities of the novel flat heat pipe without the wick, dominated by the entrainment limit, are greater and they increase with the increase in working temperature and cross-sectional diameter, and remain constant for various liquid fill levels >0.04 m.
- For the maximum heat transport capacities of both flat heat pipes with and without the wick, *n*-pentane is superior to HFE-7100.

REFERENCES

[1] Rightley MJ, Tigges CP, Givler RC, *et al*. Innovative wick design for multi-source, flat plate heat pipes. *Microelectronics J* 2003;**34**:187–94.

[2] Tan BK, Huang XY, Wong TN, *et al*. A study of multiple heat sources on a flat plate heat pipe using a point source approach. *Int J Heat Mass Transf* 2000;**43**:3755–64.

[3] Xuan Y, Hong Y, Li Q. Investigation on transient behaviours of flat plate heat pipes. *Exp Therm Fluid Sci* 2004;**28**:249–55.

[4] Wang Y, Vafai K. An experimental investigation of the thermal performance of an asymmetrical flat plate heat pipe. *Int J Heat Mass Transf* 2000;**43**:2657–68.

[5] Nakamura Y, Niekawa J, Enomoto H, Kojima Y, *et al*. Plate type heat pipe. United States Patent No. 6745825, 8 June 2004.

[6] Riffat SB, Ma X. Recent developments in heat pipe technology and applications: a review. *Int J Low-Carbon Technol* 2007;**2**:162–77.

[7] Babin BR, Peterson GP, Wu D. Analysis and testing of a micro heat pipe during steady state operation. *American Society of Mechanical Engineers*, New York, 1989, Paper 89-HT-17.

[8] Dunn PD, Reay DA. *Heat Pipes*, 3rd edn. Pergamon Press, 1982.

[9] Babin BR, Peterson GP, Wu D. Steady-state modeling and testing of a micro heat pipe. *J Heat Transf* 1990;**112**:595–601.

[10] Zhuang J. *Heat Pipe and Heat Pipe Heat Exchanger*, 1st edn. The press of Shanghai Jiaotong University, 1989, 127–30.

[11] Kraus AD, Bar-Cohen A. *Thermal Analysis and Control of Electronic Equipment*. McGraw-Hill, 1983.