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Charging of miniature flat heat pipes

Sivanand Somasundaram¹, He Bin¹, Wei Mengyao³, Chuan Seng Tan^{1,3} and Evelyn N. Wang²

¹ Singapore-MIT Alliance for Research and Technology Centre, Singapore, 138602

² Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

³School of Electrical and Electronics Engineering Nanyang Technological University Singapore

Abstract

Accurate charging of vapor chambers is critical for deriving maximum performance. In this work methods and processes to improve the evacuation and back fill technique of charging miniature vapor are described and demonstrated. A burette based charging method for charging volumes of 10 to 200 μl is described. The charging station calibrations results are discussed. The main advantages realized in the system described are better accuracy or resolution up to 2 μl , reusability of same samples for multiple filling ratios and finally a simpler process to facilitate ease of use.

Introduction

Flat heat pipes or vapor chambers are effective heat spreaders used for dissipating concentrated heat loads to larger areas. They are designed to operate at the saturated conditions i.e. a working device contains only the working fluid and the vapor in equilibrium at a given temperature. The presence of non-condensable gases will affect the condensation of water vapor. Also the amount of fluid charged has to be controlled accurately. A higher amount when injected would flood the wick structures and thin film evaporation area (formed at the edge of meniscus at every pore)

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4 would be lost. A very low amount would limit the maximum heat flux that can be spread. So the
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6 function of a charging station is to evacuate the vapor chamber to remove all non-condensable
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8 gases, to produce degassed liquid free from dissolved gases and to inject the right amount of
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10 degassed fluid into the vapor chamber.
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13 14 15 Different charging methods 16 17

18 Due to the complexity of the charging process, many researchers have attempted a
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20 method wherein the heat pipe is completely filled with charging fluid and then excess amount is
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22 removed by either boiling or by vacuum suction pressure. Such methods make the charging
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24 amount difficult to control and require lots of trial and error.
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28 A list of other different techniques and methods used so far for charging miniature vapor
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30 chambers are summarized here for reference. Gillot et al. [1] used a micro syringe based back fill
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32 technique charge silicon vapor chambers. After evacuation, a micro syringe sent the fluid
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34 through the T-joint. The charging volumes were on higher scales (0.1-0.65 ml). Cao et al. [2]
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36 described three different methods of charging techniques. Thermodynamic equilibrium method,
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38 capillary tubing method and micro syringe method. Thermodynamic equilibrium method
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40 depends on removing some amount of mass of water from the fully charged pipe until pressure
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42 equilibrium is achieved with a vacuum chamber. This method requires careful calibration for
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44 every size of heat pipe and the deviation from predicted amount was also higher. The capillary
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46 tubing method is similar to thermodynamic equilibrium method but uses a capillary tube into
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48 which the liquid is pushed from a fully filled heat pipe by heating. This is accurate than the
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50 thermodynamic equilibrium method but presence of vapor bubbles in the capillary tube will
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52 make the reading erroneous. The third method described was that of micro syringe method,
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4 which uses a syringe to feed the required quantity of fluid into an evacuated device. The feeding
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6 process has potential to affect the vacuum inside the device. Also the degassed water is forced to
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8 be exposed to air during this process. Dead volumes in the tee joints and other connectors have to
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10 be estimated to predict the actual charged amount. But the setup is easy and this most widely
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12 used so far. Oshman et al. [3] filled about 800 μl in their devices using micro-syringe method.
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14 There have been reports [4] of some interesting charging methods as well wherein first a
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16 calculated amount of working fluid is filled into the device first and subsequently the whole
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18 device is cooled by liquid nitrogen to freeze the working fluid. Then the device is evacuated to
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20 remove the non-condensable gases. The method is novel and easy to use but the effect of
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22 extreme temperature might affect the reliability of the mechanical joints in the device. Moreover,
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24 the extent of purity of working fluid (free from trapped non-condensable gases) is unknown.
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32 Ababneh et al. [5] designed a high precision charging rig capable of charging in the range of 50-
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34 500 μl . This method used custom precision burettes. The present method is an extension of this
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36 method with an aim to maintain similar accuracy and resolution with less complexity and also
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38 avoiding exposure of degassed fluid to external air/gases.
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42 Description of the charging system

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45 The present system was developed for flat or planar vapor chambers. We discuss two possible
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47 options- charging system for devices with two separate charging ports (one for evacuation and
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49 one for charging) and also of systems where there is only one port which is used both for
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51 evacuation and charging.
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The objectives of the charging station was to produce degassed water, evacuate the device to pressures of $10\text{E-}5$ mbar to $10\text{E-}6$ mbar and charge with precise amounts in the order of 10-50 μl .

Degassing

Degassing was done by freeze pump thaw cycles. To accomplish it the stainless steel tank was made of smaller diameter (50mm) so as to fit into the portable lab size 2L Dewar flasks. The tank had two tubes, one was short and mainly used for pulling vacuum and the other tube was longer (close to the base of the wall) to enable liquid dispensing. Initially clean DI water was filled in the tank and then immersed into a Dewar filled with liquid nitrogen. The pressure gauge in the degassing tank would indicate pressure drop as more liquid and vapor freeze and start freezing. After about 20 mins or so, the vacuum pump was used to pull vacuum and remove all the non-condensable. Pressures close to $10\text{E-}5$ mbar was reached. Subsequently the vacuum was isolated and the Dewar was removed and hotplate was used to heat the degassing tank to thaw the frozen liquid and the same cycle was repeated two more times to ensure high degree of degassing.

Fig. 1. Schematic of a two port charging station

Evacuation system

The evacuation system consisted of a turbo molecular vacuum pump with an oil sealed backing pump. The pump was simultaneously connected to degassing station, the evacuation port and also to burette filling lines through necessary fittings, to void frequent dismantling of connections. The tubing was standard flexible bellows (KF16) and O-ring sealed clamps. A cold

trap was placed just besides the turbo pump to avoid unnecessary water vapor or water getting into the pump. Also use of cold trap enabled reaching lower pressures at a quicker rate. Custom welded adapters are required to adapt KF 16 to the evacuation port.

Fluid dispensing system.

A custom burette of 10 μ l resolution was specially ordered. It had a maximum capacity of 3 ml. The burette was closed on the top by using a valve. The bottom of the burette was connected to a tee joint which connected the burette both to the device charging port and the line connecting to degassing tank/vacuum pump. One normal gate valve alone was placed in between the tee joint and the device to control the charging process. This reduces the complexity and dead volume associated with more valves and fittings.

Calculation of filling volume

A device with 'A' cm^2 of active wick area with wick height of 'h', and vapor gap (space in the device above the wick) 't, porosity of the wick 'p' and the volume of fill tubes (until the valves) 'V' is taken for reference calculations. The total amount of fluid to be charged corresponds to the volume of liquid required to just saturate the wick and to fill the vapor gap and the fill the tubes with vapor.

$$\text{Mass of liquid in wick, } M_l = \rho_{l,T_{\text{sat}}} * h * A * p$$

$$\text{Mass of vapor (device +fill tubes), } M_v = \rho_{v,T_{\text{sat}}} * (t * A + V)$$

$$\text{Total volume to be filled } V_{\text{fill}} = (M_l + M_v) / \rho_{l,T_{\text{amb}}}$$

Finally the amount to be dispensed from burette will correspond to the calibrated value corresponding to V_{fill} to account for dead volume of the intermediate valve.

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4 a) Two port charging system
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8 In the current demonstration, the vacuum port was designed as a 3 mm OD stainless steel
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10 tube to provide a fast evacuation of the device. The other port, used for charging is made as 1.6
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12 mm OD stainless steel tube to minimize dead volume in associated fittings and tubing. Dead
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14 volume is the extra volume that needs to be dispensed to account for fluid that gets trapped in
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16 fittings and tubing in between the dispensing system and the device. The schematic of the system
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18 is shown in Fig.1 below.
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23 A sample mounted to the charging station is shown in Fig.2. The samples as described
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25 earlier had 1/8" tube as evacuation port and 1/16" port as charging port. For 1/8 " port ,
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27 Swagelok's ultra Torr union fitting was used to connect the port to the valve. For 1/16" port a
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29 compression ferrule was fixed on the tube and directly connected to the valve. It is to be noted
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31 that use of any other intermediate fittings to connect the 1/16" port lead to unpredictable dead
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33 volumes. The supporting stands holding the valves are fixed in slotted grooves in the base stand.
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38 b) Single port charging system
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42 Sometimes fabrication and handling two separate ports for evacuation and charging can be
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44 time consuming and may add complexity. Moreover with two tubes connected to two valves, the
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46 degrees of freedom of the sample at test is reduced and these constraints can cause unnecessary
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48 stress in the sample. Charging station with single port, simultaneously used as evacuation port
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50 and fill port is shown in Fig. 3. The single port has an outer diameter of 1.6 mm and inner
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52 diameter of 1 mm. A 1/16" compression fitting T-joint is directly connected to the fill tube with
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54 the top end of the T- joint connected to the burette line through a valve and the side end
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56 connected to the vacuum line through a valve.
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This method of connection (both single port and two port system) offers the following advantages,

- 1) The same sample can be thermally tested for different filling ratios
- 2) The dead volume is minimal due to very minimal number of fittings
- 3) The same station can easily accommodate samples of different sizes easily

Fig .2. A sample mounted to charging station

Method of operation

Two port system

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4 First degassing of water is done in degassing tank as explained above. Later the valve above the
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6 sample's evacuation port alone is opened and the device is evacuated to pressures of $10E-5$ mbar.
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8 Then the valve is closed and isolated from vacuum pump. Next the valves connecting the burette
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10 to degassing tank and to vacuum pump are opened and evacuated. This step is to evacuate the
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12 outlet lines of degassing tank and the burette. After that vacuum pump is isolated. Meanwhile in
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14 parallel the degassing tank is slightly heated and pressure is built, which can pump the water out.
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16 Then the outlet valve of degassing tank is opened and the water is filled into the burette. Then
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18 meniscus reading in the burette is noted and the valve below the burette is opened slowly until
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20 the meniscus in the burette drops to the desired value. Since there is not much pressure drop
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22 between the burette and device, external gas was not required to push the liquid from burette to
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24 sample unlike in previous reports [5]. After charging, if the dispensed amount needs to be
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26 calculated for calibration or other purposes, it is disconnected from charging station and weighed
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28 in an accurate weighing scale.
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35 36 37 Single port system 38 39

40 For single port system filling of burette is same as described above for two port system. Then the
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42 valve V1 is opened to evacuate the sample and then closed. Subsequently the valve V2 above the
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44 tee joint is opened to dispense the charging fluid from burette. Most of the fluid enters the
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46 sample excluding a small amount which exits the side outlet of tee joint. The exact amount
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48 depends on the pressure level achieved after vacuum and by calibration it was observed that it
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50 remained more or less the same within a range. Due to this the accuracy of this set up is lower
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52 than the direct fill arrangement in two port set up.
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Fig .3. Schematic of single port charging station

Challenges and solutions of operating the charging station

Some of the challenges faced while operating the system are listed below:

- 1) Vacuum leak or inability to reach low vacuum levels.
- 2) Vapor bubbles in burette /overfilling of burette
- 3) Dead volume of charging valve had unpredictable values sometime
- 4) Accuracy beyond the resolution of burette (10 μ l)

The solutions adopted for the above challenges were as follows

- 1) Since there were many compression fittings any untightened part lead to poor vacuum levels. So each part was isolated using the valves and a He leak tester was used to detect the source of leakage.
- 2) The major problem while operating the station initially was that the burette could not be filled without vapor bubbles when filling from the degassing tank. Presence of bubbles in the burette makes it impossible to calculate the amount of volume dispensed. Another problem was since the total burette volume was only 3 ml it was easy to overfill the burette above the last graduation mark, which again is a hindrance to dispense calculated volume. Initially the burette was filled from the top and this lead to the presence of bubbles. However, later the system was modified as show in Fig.1. with the burette being filled from the bottom. In addition the degassing tank was heated to mild temperatures 35-45 deg C only as this will ensure that the pressure drop faced by the liquid entering the burette will not be very high and can reduce the formation of vapor bubbles. Moreover if any vapor bubbles are formed they may rise to the top of the burette, leaving a clean liquid column. Also with this modification, the fill rate was slower and overfill was easy to avoid.
- 3) It was observed that though the dead volume of the valve in the charging port was same in most cases sometimes it was different from the expected value. It was observed that this happened only during the first sample fill after the burette was filled. So we expect that there is a small volume in the valve which is neither filled with water nor exposed to vacuum until the first sample filling. This makes the dead volume more during the first (after burette being filled) initial filling. However after the first filling this volume seems to be filled with water already and the actual effective dead volume is smaller for

subsequent fills. So usually a dummy sample is used for first filling and is not used for actual calibration.

- 4) The burette that was custom made had only resolution of 10 μl . Higher resolutions are neither easily available nor easy to make. Also they will be even thinner and difficult to vacuum and the height will also be too long. So in the current set up to increase the resolution a high resolution camera (from a stand with variable height, to avoid parallax error) was used to capture the meniscus, as shown in Fig.4. By correlating the number pixels between two subsequent graduation marks volume corresponding to one pixel was calculated and dispensed volume was controlled by pixels. In this way a higher resolution was achieved.

Fig.4. Meniscus image in camera

Results

The charging station was used to dispense predetermined amounts of fluid in the range of 15 to 70 μl and the samples were weighed to establish a relationship or to quantify the dead volume.

Fig.5. shows the correlation of dispensed volume and actual volume in the device (sample).

Fig.5. Dispensed volume vs actual volume for two port configuration

Fig.6. Dispersed volume vs actual volume for one port configuration

A linear relationship was fit based on these results and when the resulting equation was used to predict the actual dispensed volume. The one port configuration had more fluctuating dead volume in the range of 10 μl as the exact amount of water that escaped through the sides of the tee joint was a strong function of the pressure and was difficult to control or predict. So the average error, defined as average of absolute deviation between the actual dispensed amount with the predicted value from linear fit of calibration data, was 4.2 μl. However for the two port

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4 configuration, the average error was less than 2.4 μl . It is estimated that the experimental
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6 uncertainties arising from uncertainty in the weighing scale ($\pm 1 \mu\text{l}$) and also from the non-
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8 repeatable nature of dead volume (estimated to be within $\pm 2 \mu\text{l}$). However, with existing
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10 methods and equipment this accuracy is reasonably good to thermally characterize the vapor
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12 chambers accurately.
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17 To understand the effect and importance of charging amount in miniature flat heat pipes, a
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19 sample silicon vapor chamber was tested at three following conditions i) empty ii) 60 μl and iii)
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21 30 μl . The sample had integrated RTD heaters and sensors in the base to simulate the heat source
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23 and also to measure the temperature. The RTD measurement in the integrated sensor indicates
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25 the evaporator temperature. The 1 cm^2 area of evaporator had four RTDs and the average
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27 temperature is calculated from the four measurements. The condenser area on the top had a water
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29 cooled heat sink. The detailed experimental set up is explained in [6].
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Fig.7. Effect of charging ratio on vapor chamber performance

For the sample under test the theoretically calculated volume to just saturate the wick with water was 30 µl. The tests of overcharged sample with 60 µl showed low performance indicating that the heat transfer mechanism was primarily through conduction. So the performance characteristic was close to that of an empty sample. However for the case with 30 µl sample which just saturated the wick led to a meniscus formation leading to thin film regions. Evaporation through these thin films is evident in Fig.7 from the lower device temperatures compared to the empty or 60 µl case.

Conclusions

A detailed description of burette based back fill techniques was described and demonstrated. The two port charging system had better accuracy than one port charging system due to more predictable dead volume. The resolution of the burette was increased by the aid of a digital camera and dispensed volumes were controlled within an error of 2 μl . The system was designed in a way that it can accommodate samples of different sizes and the sample could be tested for multiple filling ratios. The system was made simpler and did not need external gases to push the liquid from burette to the sample. However the two port charging system restricts the mechanical degree of freedom and there are more potential sources of stress which is of concern for devices made of brittle materials. The one port charging station overcomes this limitation but at the cost of lower charging accuracy. Thus the described method of charging would enable charging of vapor chambers and heat pipes easy and accurate.

Acknowledgments

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References

- [1] A. Lai, C. Gillot, M. Ivanova, Y. Avenas, C. Louis, C. Schaeffer, and E. Fournier, "Thermal characterization of flat silicon heat pipes," *Twent. Annu. IEEE Semicond. Therm. Meas. Manag. Symp. (IEEE Cat. No.04CH37545)*, pp. 21–25.
- [2] M. Gao, Y. Cao, and M. a. Zampino, "Ceramic Miniature Heat Pipes and Liquid Charging Methods," *Heat Transf. Eng.*, vol. 31, no. 7, pp. 564–569, 2010.

- 1
2
3
4 [3] C. J. Oshman, "Development, fabrication and experimental study of flat polymer micro
5 heat pipes," University of Colorado, 2012.
6
7
8
9
10 [4] J. S. Go, "Quantitative thermal performance evaluation of a cost-effective vapor chamber
11 heat sink containing a metal-etched microwick structure for advanced microprocessor
12 cooling," *Sensors Actuators, A Phys.*, vol. 121, no. 2, pp. 549–556, 2005.
13
14
15
16
17
18 [5] M. T. Ababneh, S. Chauhan, F. M. Gerner, D. Hurd, P. de Bock, and T. Deng, "Charging
19 Station of a Planar Miniature Heat Pipe Thermal Ground Plane," *J. Heat Transfer*, vol.
20 135, no. 2, p. 21401, 2012.
21
22
23
24
25
26 [6] Mengyao Wei, Bin He, Qian Liang, Sivanand Somasundaram, Chuan Seng Tan and
27 Evelyn N. Wang, "Study of Ultra-Thin Silicon Micropillar Based Vapor Chamber",
28 *Proceedings of the 3rd World Congress on Mechanical, Chemical, and Material*
29 *Engineering (MCM'17)*, DOI: 10.11159/htff17.124, June 2017.
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