ADVANCES AND OPPORTUNITIES IN BUBBLE-ACTUATED CIRCULATING HEAT PIPE (BACH)

Niro Nagai^{a*}, Akikazu Iwamoto^a, Toyoji Onishi^b, Hideo Shingu^b

^a Department of Mechanical Engineering, University of Fukui, Fukui, 910-8507, Japan

^b The Wakasa Wan Energy Research Center, Tsuruga, 914-0192, Japan

ABSTRACT

Bubble-Actuated Circulating Heat pipe (BACH) is a new type of heat pipe, which transport heat mainly by liquid circulation induced by bubble buoyancy force. BACH is strongly expected to have new features which may overcome defects on conventional heat pipes. Heat transport rates of BACH under bottom heat mode were experimentally measured under various conditions. The result shows that the heat transport rates of BACH is the order of several hundred watt and its effective thermal conductivity is $5 \sim 20 \text{ kW}/(\text{m}\cdot\text{K})$. Finally, several candidates for BACH's future application are introduced.

Keywords: heat pipe, BACH, heat transport characteristics, effective thermal conductivity, bubble

1. INTRODUCTION

Heat pipe is one of heat transport devices which can transport heat more than that by heat conduction and operates without power input. In the past, heat pipe have played important roles for thermal control system of electronic devices, efficient use of natural energy such as geothermal energy, and so on (Ohshima et al., 1979, JAHP, 2001). Conventional heat pipes can be largely classified into two types: one is wick-type heat pipe (Ohshima et al., 1979) including two-phase thermosiphon type (Ueda et al., 1988, Koito et al., 2006), and the other is self-oscillation-type heat pipe (Nishio et al., 1999, Tong et al., 2001, Suzuki, 2003, Miyakawa et al., 2005, Qu and Ma, 2007) including capillary loop type (Maydanik, 2005, Launay et al., 2007). Forced-oscillating-flow heat-pipes (Nishio and Tanaka, 2002), so called as “dream pipe”, have high performance of heat transport, but it needs power input for oscillating liquid inside.

Wick-type and self-oscillation-type heat pipes have been eagerly researched and developed for practical use. However, there are still defects on these two-types of conventional heat pipes as follows.

As to wick-type;

- Except specific type proposed by Koito et al., 2006, heat transport ability becomes very low in top heat mode, due to limit of reflux by capillary force.
- There is heat transport limit mainly due to limit of reflux by capillary force.
- Except thermosiphon type, flexibility of pipes is generally little.
- Heat transport is mainly by latent heat transport, so there is much effect of incorporation of non-condensable gas.

As to self-oscillation type;

- Pipe diameter is limited to rather small scale (less than 1 cm), since expansion and deflation of vapor bubbles inside pipe are main mechanism of heat transport.
- Except specific types (Maydanik, 2005, Launay et al., 2007), heat transport ability becomes very low in top heat mode.
- Heat transport is mainly by latent heat transport, so there is much effect of incorporation of non-condensable gas.

Bubble-Actuated Circulating Heat pipe (BACH) is recently invented by Shingu and Ohtani, 2007, in Wakasa-Wan Energy Research Center. Its appearance is just like a closed-loop thermosiphon-type heat pipe, however the operating mechanism of BACH is different from that of traditional types, judged from preliminary experiments. Figure 1 shows operating mechanism of BACH inferred from preliminary observation experiments.

- 1) Working fluid is filled in at high volume fraction, $\sim 90\%$, in a looped vacuum tube.
- 2) Temperature difference is set between heating and cooling section.
- 3) Vapor bubbles are generated constantly and stably at bubble generation part in heating section.
- 4) Unidirectional circulation flow of the fluid is induced by buoyancy force of vapor bubbles.
- 5) In addition to latent heat transport by vapor bubbles, sensible heat transport by fluid circulation is realized.

The bubble generation part located at the heating section is designed to generate vapor bubbles stably even if wall superheat of heating section is very small. As a result of preliminary experiment, it was found that working fluid in pipe flows at several tens of centimeters per second, and it was inferred that sensible heat transport was dominant judging from its rather high speed of liquid flow.

* Corresponding author. Email: nagai@u-fukui.ac.jp

Fig. 1 Operating mechanism of BACH inferred from preliminary experiments

BACH has promising characteristics as follows.

- BACH can operate not only by single component of working fluid such as water, alcohol, refrigerant liquid and so on, but also by mixed components of these fluids. By changing kinds of fluids and combination of mixed components, variability of operating temperature and performance improvement can be expected.
- Although still in preliminary experiment stage, top heat mode operation of BACH was found to work well with relatively simple contraption. If high heat transport in top heat mode is realized, BACH can be applied to practical use such as solar heat system on roof.
- BACH can operate under relatively large diameter of pipe, since it does not need capillary effect as self-oscillation type needs.
- Primary cause of heat transport of BACH may be sensible heat transport, not latent heat.

On the other hands, defects of BACH can be listed below.

- BACH cannot operate under non-gravitational field, since it utilizes buoyancy force of bubbles.
- Heat transport rates of BACH may be relatively small compared to the conventional type of heat pipe, since its heat transport is mainly sensible heat.
- Thermal design of BACH is difficult at the present moment, since heat transport characteristics is unrevealed and operating mechanism has not been verified theoretically.

Therefore, this research aims to obtain fundamental data for the grasp of operating mechanism and practical use of BACH in the future, by measuring the heat transport characteristics of BACH of bottom heat mode under various conditions. In addition, several examples of BACH's future applications are introduced and discussed.

2. EXPERIMENTAL SETUP AND METHOD

Figure 2 demonstrates schematic diagram of experimental setup for measuring heat transport rate of BACH. BACH tested consisted of two vertically-arranged stainless steel pipes whose inner diameter was mainly 14mm and outer diameter was mainly $\phi = 15\text{mm}$, and horizontally-disposed cylindrical heating and cooling section whose diameter was 50mm and length was 100mm. Heating and cooling section were placed in water bath, and its water temperature was controlled by circulating water from thermostatic bath. Vertically-arranged stainless steel pipes for adiabatic section were exchangeable. Window for observation of inside flow situation was placed on the top of cooling section just above the vertical stainless steel pipe.

Fig. 2 Schematic diagram of experimental set up for measuring steady state heat transport rate

CH1~CH5 in Fig.2 show points of temperature measurement by T-type thermocouples. Temperature of CH1 and CH2 corresponds to inlet and outlet temperature of cooling water which flows into water tank of cooling section. Heat transport rate, Q (W), under steady state condition can be estimated by Eq. (1).

$$Q = \dot{m}c \cdot \Delta T_c \quad (1)$$

where $\dot{m}$ is mass flow rate of cooling water (kg/s), c is specific heat at constant pressure (J/(kg·K)), ΔT_c is temperature difference between inlet(CH1) and outlet(CH2) of cooling water. Mass flow rate was obtained by measured volume flow rate and density of water. Estimated heat transport rate, Q , included $\pm 30\%$ uncertainty, mainly due to measurement error of temperature difference, ΔT_c . The water temperature in water tank around cooling section, T_c , was evaluated as average temperature of inlet(CH1) and outlet(CH2) of cooling water. The water temperature in water tank around heating section, T_h , was directly measured at CH5. Temperatures measured at CH3 and CH4 were wall temperature of cooling section, T_{wc} , and heating section, T_{wh} , respectively. All data for temperature of CH1~CH5 were averaged during 5 minutes after steady state condition was achieved.

The followings were the experimental parameters.

- Kind of working fluid water, ethanol
- Water temperature in water bath
 (around cooling section) $T_c = 10^\circ\text{C}, 20^\circ\text{C}$
 (around heating section) $T_h = 50 \sim 90^\circ\text{C}$
- Liquid volume fraction $\alpha = 30 \sim 90\%$
- Pipe length (adiabatic section)
 $L = 200\text{mm}, 500\text{mm}, 1000\text{mm}$
- Pipe diameter (adiabatic section)
 $\phi = 15\text{mm}, 20\text{mm}$

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 General Heat Transport Characteristics of BACH

Figure 3 shows general heat transport characteristics of BACH for water and ethanol as working fluid, and water temperature in cooling section $T_c = 10^\circ\text{C}, 20^\circ\text{C}$. Abscissa of Fig.3, ΔT , denotes temperature difference between hot water temperature, T_h , and cold water temperature, T_c . Within the range of this experiment, heat transport rate of BACH was found to be several hundred watt for both water and ethanol in case of pipe diameter $\phi = 15\text{mm}$, pipe length $L = 500\text{mm}$ and liquid volume fraction $\alpha = 75\%$. As mentioned in INTRODUCTION, there were misgivings the heat transport rate of BACH is very little compared to conventional type heat pipe, since dominant operating mechanism of BACH is considered to be sensible heat transport. The

heat transport rate of conventional heat pipe (thermosiphon type) of pipe diameter $\phi = 20\text{mm}$ was reported by Oshima et al., 1979, to be about 400W in case of $T_h = 50^\circ\text{C}$ and $T_c = 0^\circ\text{C}$, and about 700W in case of $T_h = 60^\circ\text{C}$ and $T_c = 0^\circ\text{C}$. Therefore, it was found that BACH has about 50% of heat transport ability of thermosiphon heat pipe when the working fluid is water and ethanol.

Fig. 3 Heat transport rate of BACH

Figure 3 also demonstrates the followings. (i) Heat transport rate, Q , increases monotonically as temperature difference, ΔT , (i.e. hot water temperature, T_h) increases. (ii) The heat transport rate at $T_c = 20^\circ\text{C}$ is larger than that of $T_c = 10^\circ\text{C}$ at the same temperature difference. (iii) There is relatively little difference of heat transport rate between water and ethanol, regarding much difference of latent heat of evaporation between these two liquid. These results are consistent with the inference that sensible heat transport is dominant for BACH.

3.3 Effect of Liquid Volume Fraction

As shown in Fig.4, liquid volume fraction, α , affected heat transport rate, Q . The heat transport rate takes maximum value when the liquid volume fraction $\alpha = 30\%$. Although the heat transport rate decreases as liquid volume fraction increases, its tendency changes from $\alpha = 75\%$, i.e. the heat transport rate increases as liquid volume fraction increases.

Fig. 4 Relation between liquid volume fraction and heat transport rate

Judging from visual observation, this result can be explained as follows. In case of $\alpha < 75\%$, liquid part of working fluid does not circulate inside pipes, which means this heat pipe operates not as BACH but as conventional thermosiphon type heat pipe. However, in case of $\alpha \geq 75\%$, sensible heat transport is performed by circulation of liquid part of working fluid and then it operates as BACH. Condition of liquid volume fraction $\alpha = 75\%$ corresponds to that when a little amount of liquid part of working fluid exists in the horizontal pipe of cooling section.

Figure 4 also indicates that operating mode as BACH can be continuously changed to that as conventional thermosiphon type heat pipe, by changing liquid volume fraction.

3.4 Effect of Pipe Length (adiabatic section)

Figure 5 shows the heat transport rate in case of water, $T_c = 20^\circ\text{C}$, $\alpha = 75\%$ and $T_h = 40 \sim 90^\circ\text{C}$, with pipe length of adiabatic section $L = 200\text{mm}$, 500mm , 1000mm . This result demonstrates the followings. (i) There is little change of qualitative tendency in case of changing the pipe length that heat transport rate increases as hot water temperature increases. (ii) Compared experimental results of $L = 500\text{mm}$ to that of $L = 1000\text{mm}$, there is little change of the heat transport rate at each hot water temperature. However, only in case of $L = 200\text{mm}$, the heat transport rate is about 50W higher than that of $L = 500\text{mm}$, 1000mm .

Fig. 5 Relation between pipe length of BACH and heat transport rate

These results implies that flowing velocity of working fluid becomes faster in case of $L = 200\text{mm}$ for some reasons. Friction loss of pipe flow, buoyancy force induced by generated bubbles, bubble condensation and other related phenomena are involved to this matter, so verification experiments such as measuring the flowing velocity and bubble frequency are necessary in the future.

3.5 Effect of Pipe Diameter

Fig. 6 Relation between pipe diameter of BACH and heat transport rate

Figure 6 shows the heat transport rate in case of water, $T_c = 20^\circ\text{C}$, $\alpha = 75\%$, and $L = 500\text{mm}$, with pipe diameter $\phi = 15\text{mm}$, 20mm . As a result, heat transport rate of $\phi = 20\text{mm}$ is about 0.15kW higher than that of $\phi = 10\text{mm}$. Just like effect of pipe length, several phenomena such as friction loss of pipe flow, buoyancy force induced by generated bubbles, bubble condensation, and so on may relate to this influence of pipe diameter.

3.6 Thermal Resistance

Thermal resistance is one of often used parameters for exhibiting heat transport characteristics of heat pipe. Here, thermal resistance between heating and cooling section, R_w , is defined by Eq. (2).

$$R_w = \frac{T_{wh} - T_{wc}}{Q} \quad (2)$$

where T_{wh} is wall temperature of heating section and T_{wc} is wall temperature of cooling section, respectively. Figure 7 shows the relation between thermal resistance, R_w , and hot water temperature, T_h , in case of water, ethanol, $T_c = 10^\circ\text{C}$, 20°C , $\alpha = 75\%$, $L = 500\text{mm}$, and $\phi = 15\text{mm}$. The thermal resistance was found to be the value of $0.1 \sim 0.3\text{K/W}$ within this experimental condition. There is a tendency that thermal resistance decreases with increase of hot water temperature.

Fig. 7 Thermal resistance of BACH

Total thermal resistance between hot water and cold water, R_{total} , which can be estimated by substituting T_h to T_{wh} and T_c to T_{wc} in Eq.(2), was found to be as twice as the thermal resistance of BACH, R_w . Thermal resistance difference between R_{total} and R_w corresponds to thermal resistance of convection heat transfer between wall surface of each heating and cooling section and its surrounding water. This result means thermal resistance of BACH, R_w , is almost same order of that of convection heat transfer, which implies that main cause of thermal resistance inside BACH is forced-convection thermal resistance. If thermal resistance inside BACH is confirmed as forced-convection thermal resistance by further verification research, it is efficient to install heat transfer enhancement device such as a fin inside BACH for decreasing thermal resistance of BACH.

3.7 Effective Thermal Conductivity

As another parameter showing heat transport characteristics of heat pipe, effective thermal conductivity is also frequently used. Figure 8 shows the relation between effective thermal conductivity λ_{eff} and hot water temperature in case of water, ethanol, $T_c = 10^\circ\text{C}$, 20°C , $\alpha = 75\%$, $L = 500\text{mm}$, and $\phi = 15\text{mm}$. The effective thermal conductivity is defined by Eq. (3).

$$\lambda_{eff} = \frac{Q \cdot L_{total}}{A \cdot \Delta T_w} \quad (3)$$

where, L_{total} is overall length from bottom to top head of BACH, A is cross-section area of pipes of adiabatic section (totally for two pipes), ΔT_w is temperature difference between heating section and cooling section ($= T_{wh} - T_{wc}$). Thermal conductivity of copper ($386\text{W}/(\text{m}\cdot\text{K})$) is also shown in Fig.8.

Fig. 8 Effective thermal conductivity of BACH

From Fig.8, effective thermal conductivity λ_{eff} of BACH was found to be $5 \sim 20 \text{ kW}/(\text{m}\cdot\text{K})$. In particular, λ_{eff} of water is up to 55 times higher than that of copper. And λ_{eff} of ethanol is up to 4 times higher than that of looped capillary heat pipe reported by Miyakawa et al., 2005. In case the pipe length of adiabatic section is changed to $L = 1000\text{mm}$, λ_{eff} shows the highest value, and it is about 90 times higher than that of copper.

3.8 Discussion on Bubble Generation Part

Bubble generation part, shown in Fig.1 and Fig.2, is simple structure but most important device for BACH in order to generate vapor bubble stably. In this experiment, diameter of the bubble generation part was set to $d = 15\text{mm}$, and always contained gas or vapor inside.

According to conventional boiling theories, summarized by Carey, 1992, necessary liquid superheat, ΔT_{sat} , to generate a vapor bubble of curvature radius, r ($= d/2$), can be easily estimated as follows. Laplace equation, Eq.(4), denotes pressure difference, Δp , between vapor bubble, p_v , and surrounding liquid, p_l .

$$\Delta p = p_v - p_l = \frac{2\sigma}{r} \quad (4)$$

where σ is surface tension.

Clapeyron-Clausius equation leads to the following Eq.(5), which shows liquid superheat, ΔT_{sat} , corresponding to pressure difference, Δp .

$$\Delta T_{sat} = \frac{(\rho_l - \rho_v) T_{sat}}{\rho_l \rho_v L_{lv}} \Delta p \quad (5)$$

where ρ_l , ρ_v are density of liquid and vapor, respectively, L_{lv} is latent heat of evaporation, and T_{sat} is saturation temperature at liquid pressure, p_l .

Eq.(4) and (5) lead to the following equation, which shows relationship between liquid superheat, ΔT_{sat} , and bubble radius, r .

$$r = \frac{2\sigma T_{sat}}{\rho_v L_{lv} \Delta T_{sat}} \quad (6)$$

Figure 9 shows critical vapor bubble radius of water and ethanol estimated by Eq.(6). As surface roughness of metal of commercial use is the order of $1 \sim 10\mu\text{m}$, as shown in Fig.9, the necessary liquid superheat, ΔT_{sat} , reaches several K to 20 K for water and ethanol. However, the diameter of bubble generation part of BACH is 15mm , which corresponds to bubble curvature radius, r , about 7mm , so necessary liquid superheat becomes almost zero, below the order of 0.1K , as shown in Fig.9. Therefore, the bubble generation part of BACH can generate vapor bubbles with such a very little liquid superheat, which leads to stable and constant bubble generation.

Fig. 9 Effective thermal conductivity of BACH

4. FUTURE OPPORTUNITIES IN BACH

Heat transport characteristics of BACH in bottom heat mode were discussed in the previous section. Based on the information on this new type heat pipe BACH obtained so far, the authors and cooperators have planned the following “Research and Development Projects of BACH”, some of which have been completed and some are still under execution.

As to scientific aspects on BACH,

- to know heat transport characteristics of BACH in top heat mode,
- to understand effects of mixed components of working fluid onto heat transport characteristics,
- to establish physical modeling of BACH for both bottom-heat and top-heat mode, based on fundamental principles of heat transfer and fluid dynamics, not based on experimental correlations,
- to find out how to enhance heat transport of BACH, especially on optimum design of bubble generation part,

are our targets in order to enable to design this new type of heat pipe BACH for any conditions.

As to engineering and application aspects on BACH, the following verification and feasibility tests have been planned and conducted.

- air conditioning system, i.e. cooling in summer and heating in winter, with heat exchange between underground soil and building on the ground, by utilizing BACH with little electric power consumption,
 - anti-freezing and defrosting system in winter by BACH without electricity,
 - waste heat and solar heat utilization system, mainly in summer, by BACH in heat transport of long distance,
- and
- snow melting system of underground fire cistern by BACH.

Top-heat mode BACH is basically working well for laboratory experiments. If the top-heat mode BACH is proved theoretically and successfully verified after several years, this BACH is expected to be used as wide variety of applications such as listed above. In this paper, however, as one of applications of bottom-heat mode BACH, the last example of BACH’s application candidate, snow melting system of underground fire cistern, is introduced.

A fire cistern, i.e. water tank for fire extinction, is usually embedded into underground. The fire cistern has an opening to ground surface, made of steel top, as shown in Fig.10. In winter season at snowy and frigid regions, firemen were sometimes confronted by difficulties of finding the exact position of the steel top and opening the frozen steel top, due to much remained snow on the top and temperature below 0 °C near the ground surface. In order to deal with these difficulties, the authors and colleagues proposed a new idea

utilizing heat pipe BACH as shown in Fig.10 : i.e. BACH transport heat from water inside the cistern underground to the steel top near ground surface, for melting snow on it and heating it for anti-freezing, without consuming electric power.

Fig. 10 Outline of snow melting system around steel top of fire cistern underground using a heat pipe BACH

The fire cistern used for field tests was 40 m³ of water capacity made of silica-rock aggregate concrete, which has relatively high thermal conductivity. Its inner size was W6.8 m × D3.0m × H2.0m, with 0.2 m thickness. Covering depth of the fire cistern was 0.8 m. The fire cistern was constructed at Ohno city where it has heavy snow fall in winter. Figure 11 shows the BACH used for the field tests. BACH was made of 20A SUS304 pipe, inner diameter 23 mm, and total length was about 4 m. The working fluid was HFC-134a, which was filled into BACH with 40% of liquid volume fraction. The bubble generation part was attached at heating section as shown in Fig.11. The cooling section of BACH, which looks like loop circle, was embedded in the snow melting panel made of concrete, as shown in Fig.10. The panel was W1.0 m × D1.0m × H0.2m, with steel top of 0.6 m diameter set at center of the panel. The heating section of BACH was set inside the fire cistern, always surrounded by water. BACH absorbs heat from water through the heating section and dissipates heat through the cooling section to the panel. The intermediate section of BACH between cooling and heating section was thermally insulated. For comparison, conventional heat pipe, thermosiphon heat pipe, was also installed at the same fire cistern. The working fluid of thermosiphon heat pipe was also HFC-134a, and its diameter and length were almost the same with BACH

Figure 12 demonstrates snow melting situations on the snow melting panel at noon on December 31, 2009, in Ohno city. The weather condition at that day in Ohno city was relatively severe there, minimum temperature -1.7 °C, maximum temperature 3.0 °C, maximum natural snow depth 60 cm. In this winter season, we had heavy snowfall. As clearly shown in Fig.12, snow right above the

Fig. 11 Photo of BACH installed in the tested snow melting system

cooling section of BACH was successfully melted so that firemen can easily find the position of the steel top, in spite that the snow on the steel top was not totally melted. Especially, the snow around steel top of BACH side was satisfactorily melted compared to that of thermosiphon side. This difference is considered to come from difference of heat transport characteristics between BACH and thermosiphon heat pipe. In this way, BACH is proved to be useful for the snow melting system of fire cistern in snowy and frigid region.

Fig. 12 Photo of snow melting situation around noon on Dec.31, 2009 at Ohno city

5. CONCLUSIONS

A new type of heat pipe, named as “Bubble-Actuated Circulating Heat pipe (BACH)”, was proposed. The bubble generation part of BACH can generate vapor bubbles stably, and generated bubbles induce circulating fluid flow inside by buoyancy force. Heat transport characteristics were experimentally investigated with changing kinds of liquid, temperature of heating and cooling section, pipe length, pipe diameter, and liquid volume fraction. The results show that heat transport rates of BACH is the order of several hundred watts. The effective thermal conductivity of BACH was found to be 5 ~ 20 kW/(m · K). In addition, future opportunities in BACH are illustrated. Especially, as one of applications of bottom-heat mode BACH, snow melting system of underground fire cistern using BACH, is introduced.

ACKNOWLEDGEMENTS

This research was sponsored and supported by Promotion of Science and Technology in Regional Areas, City Area Program “Fukui-Wakasa Area”, 2008 – 2010, of the Ministry of Education, Culture, Sports, Science & Technology, Japan. The authors would like to appreciate the following companies, with whom we have conducted cooperative research on BACH ; i.e. Hokukon Co.,Ltd, Kyouwa Manufacturing Co.,Ltd, Matsumoto Tekkosyo Limited Liability Company, Nac KS Co.,Ltd, and Fukusen Co.,Ltd. The authors also would like to appreciate so much to the following expert researchers in this field, for attending “International Heat Pipe Seminar for BACH” on March 6, 2009, in Tsuruga city, and giving us valuable comments and suggestions on BACH ; Prof. Amir Faghri, University of Connecticut, Prof. Aliakbar Akbarzadeh, RMIT University, Dr. Ioan Sauciu, Intel Corporation, and Prof. Isao Kataoka, Osaka University.

NOMENCLATURE

A	cross-section area of pipes of adiabatic section, totally for two pipes, (m ²)
c	specific heat of water (J/(kg·K))
$\dot{m}$	mass flow rate of cooling water (kg/s)
L	pipe length of adiabatic vertical part in BACH (m)
L_v	latent heat of evaporation (J/kg)

p	pressure (Pa)
Q	heat transport rate of BACH (W)
r	curvature radius of vapor bubble in superheated liquid (m)
R_w	thermal resistance between heating and cooling section of BACH (K/W)
T	temperature (K)
T_c	water temperature in water tank around cooling section (K)
T_h	water temperature in water tank around heating section (K)
T_{wc}	wall temperature of cooling section of BACH (K)
T_{wh}	wall temperature of heating section of BACH (K)

Greek Symbols

α	liquid volume fraction inside BACH (-)
ΔT	water temperature difference ($=T_h - T_c$) (K)
ΔT_c	temperature difference between inlet and outlet of cooling water (K)
ΔT_{sat}	liquid superheat (K)
ΔT_w	temperature difference between heating section and cooling section ($=T_{wh} - T_{wc}$) (K)
ϕ	outer pipe diameter at adiabatic vertical part in BACH (m)
λ_{eff}	effective thermal conductivity of BACH (W/(m·K))
ρ	density (kg/m ³)
σ	surface tension (N/m)

Subscripts

l	liquid
sat	saturated condition
v	vapor

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