JP Journal of Heat and Mass Transfer
Volume 5, Number 2, 2011, Pages 149-168
Published Online: September 6, 2011
This paper is available online at http://pphmj.com/journals/jphmt.htm

LAMINAR CONDENSATION IN POROUS MEDIA WITH AMBIENT TREATMENTS

EKO SISWANTO[1,2], HIROSHI KATSURAYAMA[1] and YASUO KATOH[1]

[1]Science and Engineering, Mechanical Engineering Department
Yamaguchi University
2-16-1 Tokiwadai, Ube, Yamaguchi 755-8611, Japan

[2]Mechanical Engineering Department
Brawijaya University
Malang, Indonesia
e-mail: m505wc@yamaguchi-u.ac.jp
eko_s112@ub.ac.id

Abstract

Laminar condensation in porous media, considering thermal and effective thermal conductivity, treated by ambient temperature is experimentally studied. The aim of this study is to observe behavior of the transferred heat and the extracted condensate to determine both the effective- and the efficient-condensation via condensate thickness and heat flux ratio on the system. This test is conducted by streaming the humidified-air over the upper-face of porous glass-beads and alumina-balls media, in a chamber covered by the controlled ambient temperatures. The humid air is varied in temperature and held on laminar flow. As for first treatment, ambient temperature is maintained constantly, whereas for the next treatment, temperature ratio of ambient to humid-air is kept unity. In this study, based on the Jacob number evaluation, it can be found that the heat transfer dominates to

Keywords and phrases: laminar, condensation, porous media, ambient treatment.

Received July 10, 2011

control the condensation, whereas the inertia force plays a minor influence. Treatment-I affects significantly to condensate thickness, together with vapor concentration and thermal conductivity of media layer. Furthermore, by using heat flux ratio calculation, it is obtained that the glass beads media under treatment-I lies on the highest ratio.

Nomenclature

A_p : Area of interface $[\mathrm{m}^2]$

b_{ld} : Diffusion parameter [-]

Cp_h : Heat capacity of humid air $[\mathrm{J/kg \cdot K}]$

Cp_l : Heat capacity of condensate $[\mathrm{J/kg \cdot K}]$

d_b : Average thickness, back-view $[\mathrm{m}]$
$= (d_{bu} + d_{bl})/2$

d_f : Average thickness, front-view $[\mathrm{m}]$
$= (d_{fu} + d_{fl})/2$

H_L : Condensation number [-]

Ja : Jacob number [-]

k_{eff} : Overall effective thermal conductivity of media layer $[\mathrm{W/m \cdot K}]$

k' : Effective thermal conductivity of media, with condensate-void $[\mathrm{W/m \cdot K}]$

k'' : Effective thermal conductivity of media, with air-void $[\mathrm{W/m \cdot K}]$

Ku : Kutaleladze number [-]
$= Cp_h(T_h - T_w)/L$

m	: Mass flow rate $[\text{kg/s}]$
l	: Characteristic length $[\text{m}]$
L	: Latent heat of condensation $[\text{J/kg}]$
Le	: Lewis number $[\text{-}]$
q_c	: Heat flux supplied by vapor to interface $[\text{W/m}^2]$
	$= -k_{eff}\ dT/dz$
q_j	: Heat flux consumed by vapor condensation $[\text{W/m}^2]$
	$= mL/A_p$
Q_w	: Total heat flux cross interface $[\text{W/m}^2]$
Re	: Reynolds number $[\text{-}]$
	$= U_h l/\upsilon_h$
T	: Porous bed temperature $[°\text{C}]$
T_a	: Ambient air temperature $[°\text{C}]$
T_c	: Cooler water temperature $[°\text{C}]$
T_f, T_b, T_t	: Temperature of front, back, top of wall $= \sim T_a$ $[°\text{C}]$
T_h	: Humid air temperature $[°\text{C}]$
T_s	: Interface temperature $[°\text{C}]$
T_w	: Wall temperature $[°\text{C}]$
	$= [T_c + (T_f + T_b + T_t)]/4$
U_h	: Velocity of humid air $[\text{m/s}]$
V_c	: Vapor concentration $[\text{kg/kg}_{\text{air}}]$

z	:	Height of porous layer $[\mathrm{m}]$
δ	:	Dimensionless of condensate thickness $[-]$
ρ_l	:	Density of condensate $[\mathrm{kg/m^3}]$
ρ_v	:	Density of humid air $[\mathrm{kg/m^3}]$
υ_h	:	Kin. viscosity of humid air $[\mathrm{m^2/s}]$
μ_L	:	Dyn. viscosity of condensate $[\mathrm{Pa.s}]$

Subscripts

bl	:	back-lower
bu	:	back-upper
fl	:	front-lower
fu	:	front-upper
I	:	Treatment-I, $T_a = 35$ $[°\mathrm{C}]$
II	:	Treatment-II, $T_a/T_h = 1$

1. Introduction

To be able to control humidity of air in any specific engineering applications, exploring study in condensing moist from air to reach a good control-response to a desired humid is a crucial stage. Due to ability in extracting moist and vice versa, simple step in distinguishing liquid- and gas-phase, and prosperity in transferring both heat and mass, porous media is able to be an important alternative device to do the duties.

After heat transfer rates in laminar film condensation on the underside of horizontal and inclined-surfaces was conducted [1], in the case of absence of porous media, laminar condensation on upper-side on a horizontal perforated plate, with and without considering suction effect, has already been mathematically worked [2]. Furthermore, a more comprehensively computational analysis on condensation on a horizontal surface taking account combination of heat and mass transfer, flow of moist-air mixture, and condensed vapor over the surface was done [3].

In the presence of the porous media, the extensive condensation on laminar flow on horizontal flat surface has been analytically carried out [4]. Recently, developed from the previous study, investigation of laminar film condensation on a horizontal plate under a porous media bed was analyzed [5]. These investigations expressed the relation of the liquid film thickness on the bottom of the bed with the surface tension effects. Other information from the investigation was mentioned that the plate was also applied to be a containment of the condensate, and was designed borderless. Hence, the condensate could run over freely from the system while they reached the maximum limit. However, for all of the above theoretical investigations, it can be noted that they studied in two dimensional (2d) views consideration and omitted ambient temperature influence.

Experimentally, condensation in the horizontal porous-media layer in a chamber under laminar convection has been investigated [6, 7]. These experiments were carried out to extract condensate from moist-air mixture intended to control humidity on fuel-cell application purpose. In these studies, the extracted condensate on the flat plate under porous media was measured using the needle probe method. And then, the method has been improved [8] by using visualization. However, these works were also conducted by neglecting the ambient temperature effects, and the visualization was shot only to front-view of the test section. Therefore, those studies could not view backside, i.e. other side, of the condensate distribution or penetration.

Based on the above mention, it can be stated that the previous studies on condensation in porous media in both analysis and experiments still neglected the ambient temperature. Therefore, this study proposes that the condensation be treated by ambient temperature. With respect to the purpose of this current study, that is, to control humidity, the extracted condensate shall be able to re-evaporate as well. It means that the porous bed layer is also become a condensate-storage. For this storage reason, the non-perforated chamber in this condensation is applied. Hence, to evaluate the effects of thermal conductivity, the porous media particle used in this study are glass beads and alumina balls. Furthermore, visualization appearing condensate distribution and penetration in the observation is shot from 3d views, i.e., front-, back- and top-view.

2. Experimental Method

In this study, schematically shown in Figure 1, the porous media was occupied 20mm × 20mm × 240mm in the transparent condensation chamber. Properties of glass and alumina particles are shown on Table 1. Based on a test, porosity of these media is about 38%.

Table 1. Particle properties

Particle (name)	Average particle diameter [mm]	Density $[g/cm^3]$	Thermal conductivity [W/m°K]	Material
Glass beads	1.0	2.60	1.035	Soda glass
Alumina balls	1.0	3.61	18.84	Al_2O_3 :94.5% SiO_2 :5.5%

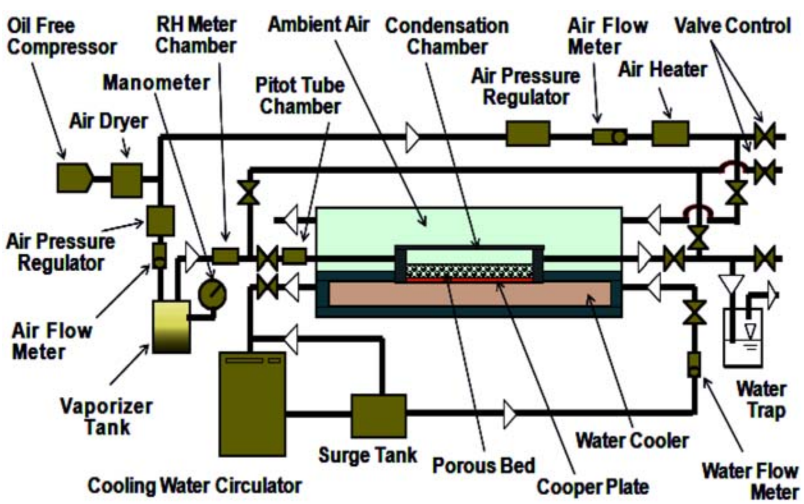

Figure 1. Schematic of experimental apparatus.

A copper plate is installed as a heat exchanger from media to the cooling water. The humid-air temperatures T_h , 35, 40, 45, 50 and 55°C, respectively at 99 RH%, were then streamed over the upper-face of the bed of media. Outside of the condensation chamber, two treatments of ambient temperature were applied. The first one, the ambient temperature was kept at $T_a = 35°C$. Secondly, the temperature ratio of ambient to humid-air was maintained at $T_a/T_h = 1$.

Oil-free compressor assures that air supplied to all of system were clean and uncontaminated. For the humid air system, the compressed air was forced to humidifier tank. Combination between the compressed air and the variation of humid-air temperature resulted pressure of the tank as $70 \sim 120\text{mm } H_2O$.

For the ambient system, a regulated pressure 0.175 MPa of air at capacity 40 liter/minute was heated by a controlled air-heater to produce the desired temperatures. Valve-controls were used to blow the transient gas conditions out before starting the observation and to guarantee that the humid- and ambient-air were in stable at desired condition. A water trap tank was required to reduce shock condition, i.e. pressure and temperature, while it contact with atmosphere. To maintain copper plate temperature, the 750 CCM of $T_c = 10$ °C water was circulated by a water-cooler package attached by a surge tank.

To observe the extracted condensate distribution and behavior, the video camera was installed to visualize front-, back- and top-view of the transparent condensation chamber for 60 minutes observation.

3. Results and Discussion

3.1. Condensate thickness

3.1.1. Effect of vapor concentration

Firstly, as a main condensation parameter, average dimensionless of extracted condensate thickness δ in porous bed (shown in Figure 2) based on the condensate distribution is calculated as follows:

$$\delta = (d_f / z + d_b / z)/2. \tag{1}$$

As for sample, the front- and back-view of the distribution in condensation chamber are shown in Figures 3 and 4, respectively. In general, Figure 2 depicts the extracted condensate thickness δ ascends with the increasing of water vapor concentration V_c, for all of treatments and media. It can be understood that the increase of the V_c means higher volume and weight of contained moist in the mixture. Therefore, the higher moist in the mixture means the higher availability of condensed moist from the mixture.

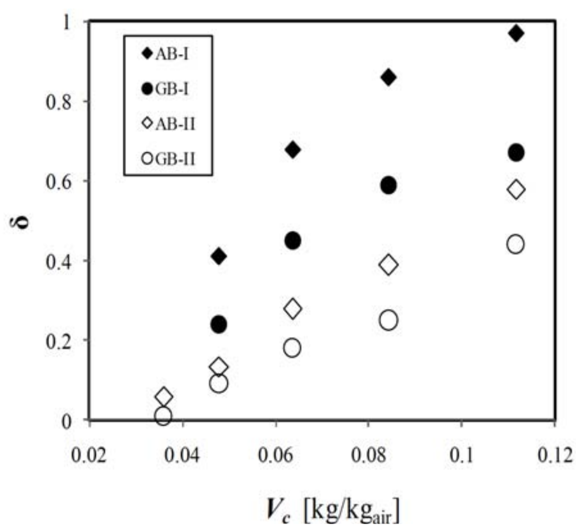

Figure 2. Relation between δ and vapor concentration.

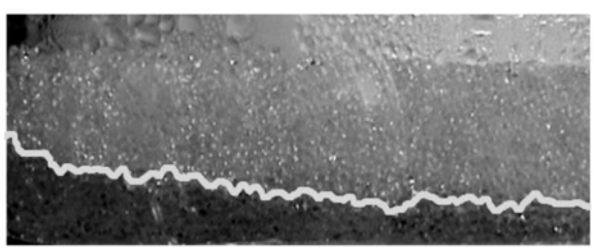

Figure 3. Front-view of condensate thickness in GB (I).

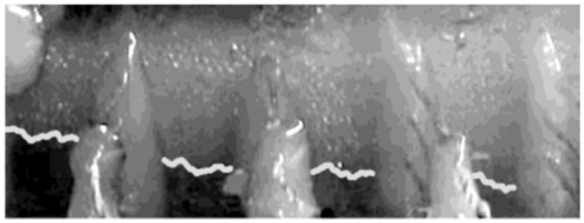

Figure 4. Back-view of condensate thickness in GB (I).

If started from $T_h = 40°C$, where the both treatments begin to exist, Figure 5 can confirm that humid air temperature T_h, where vapor concentration V_c is the function of T_h, also increases the extracted condensate δ. The relationship can be compromised linearly on both media. It indicates that toward initial thickness, that is, δ_{GBa} or δ_{ABa}, the ascending of the condensate on respective $\delta_{GB\text{-}I}$ or $\delta_{AB\text{-}I}$ due to vapor concentration or humid air temperature is relatively similar. The same case are also shown on δ_{GBa} or δ_{ABa} towards $\delta_{GB\text{-}II}$, or $\delta_{AB\text{-}II}$, therefore, they prove that in the same treatment, the vapor concentration affects to a similar ascending of the extracted condensate δ on both alumina (AB) and glass (GB) media.

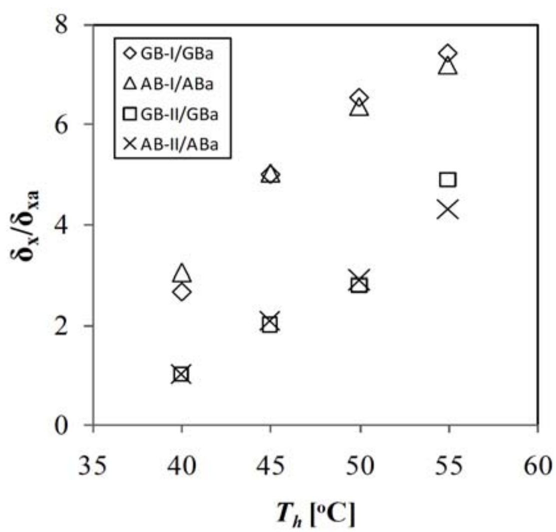

Figure 5. Ratio of condensate thickness and initial thickness on respective media.

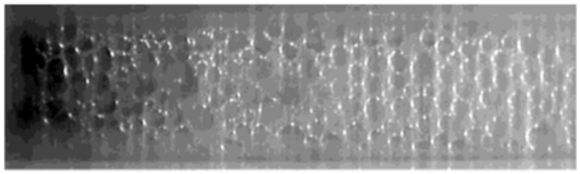

Figure 6. Dropwise from top-view of condensation chamber on GB in $T_h = 55°C$ (I).

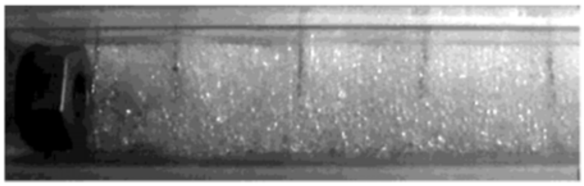

Figure 7. Absence of dropwise from top-view of condensation chamber on GB in $T_h = 55°C$ (II).

Based on Figures 6 and 7, respectively, that is much more dropwise on the walls and ceiling of condensation chamber in treatment-I but almost absence of dropwise-condensate in treatment-II, it can be concluded that heat fluxes (as condensation generator) in the treatment-II can only cross through porous media, not through the walls. Compared with the analytical study in [3], where the heat fluxes also flew only through the surface-plate, the increase of δ due to V_c on the treatment-II in this current study agree with the theoretical study. In the study, it was explained that the produced condensate was depended on diffusive parameter on the humid air mixture, where the diffusive parameter was only influenced by the weight concentration of the mixture components. In this current study, the weight concentration is represented by the vapor concentration V_c.

3.1.2. Effect of treatments

Under the same media and vapor concentration, Figure 2 also depicts that the treatment-I is in higher extracted condensate δ than the treatment-II. The different result of the condensate under the respective treatments can be explained also based on visualized evidence in Figure 6 and Figure 7. From the both evidences, it is understood that the higher condensate δ in the treatment-I due to the produced condensate is not only gained by condensation on the interface between humid air and upper face of porous media, but also resulted by dropwise on the walls of chamber, as shown in Figure 6. It can be explained that under the same V_c (also T_h), all of the "duct walls" (i.e. side-walls, ceiling and porous bed upper-face) of the condensation-chamber for treatment-I can generate condensation; whereas for treatment-II, condensation occurs effectively only on the porous bed upper-face or interface.

Related with the dropwise, they occur on the walls (and ceiling) due to condensation can happen on the walls. It is caused by heat fluxes can across through the walls. The phenomenon is caused by existence of temperature difference between the humid air inside the chamber and the ambient air outside the chamber. Hence, as additional information based on the heat flux, the treatment-II can be then stated as pure condensation over the porous media. It is due to the heat fluxes across only through the media.

It is also confirmed by Figure 5, under the same humid air temperatures (or vapor concentration) and the same media, e.g., glass beads (GB), the $\delta_{GB\text{-}I}/\delta_{GBa}$ occupy higher points than that the $\delta_{GB\text{-}II}/\delta_{GBa}$. It means treatment-I on glass media can enhance the δ than the treatment-II. Similar situation is also shown on $\delta_{AB\text{-}I}/\delta_{ABa}$ toward $\delta_{AB\text{-}II}/\delta_{ABa}$, therefore, they can reveal that the treatment-I increases the produced condensate regardless of whether in alumina or glass media. Furthermore, with paying attention to almost coincidence points between glass beads $(\delta_{GB\text{-}I}/\delta_{GBa})$ and alumina balls $(\delta_{AB\text{-}I}/\delta_{ABa})$ under treatment-I, it can be stated that the treatment-I play a same role in the extracted condensate on the both media. Moreover, it indeed, a compromise treatment-II $\delta_{GB\text{-}II}/\delta_{GBa}$ or $\delta_{AB\text{-}II}/\delta_{ABa}$ towards the previous treatment, that is, $\delta_{GB\text{-}I}/\delta_{GBa}$ or $\delta_{AB\text{-}I}/\delta_{ABa}$ happen, however, the points of the both $\delta_{GB\text{-}II}/\delta_{GBa}$ and $\delta_{AB\text{-}II}/\delta_{ABa}$ are lower than that the both $\delta_{GB\text{-}I}/\delta_{GBa}$ and $\delta_{AB\text{-}I}/\delta_{ABa}$, respectively. So that, based on the occupation points, they can be informed that the ambient treatment-I influence more significantly than that ambient treatment-II towards the produced condensate.

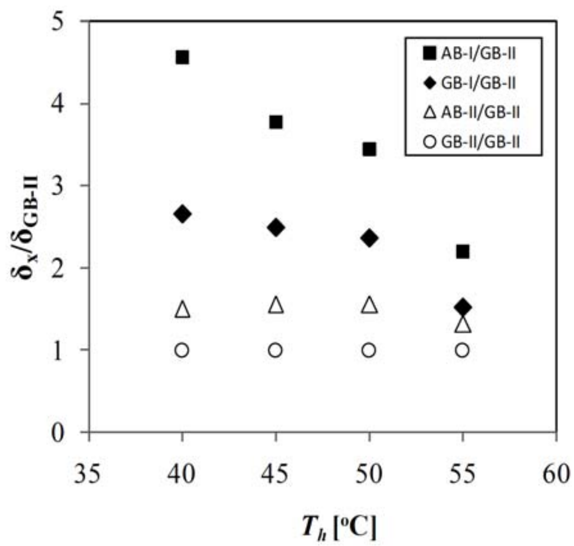

Figure 8. Ratio of condensate thickness in any media and condensate thickness in GB-II.

Finally, the role of treatment on the same media can be shown in detail in Figure 8. Toward the δ on the GB-II, where the δ is the smallest and being a reference $(\delta_{GB\text{-}II}/\delta_{GB\text{-}II})$, the treatment-I gives an average 2.26 times increase in glass beads $(\delta_{GB\text{-}I}/\delta_{GB\text{-}II})$ media. For the alumina media, the treatment-I is able to enhance average 3.49 times, shown on $\delta_{AB\text{-}I}/\delta_{GB\text{-}II}$ points.

3.2. Heat transfer and inertia force

In condensation regarding moist air flow, it is important to determine effect of major term, that is, heat transfer due to thermal effect and inertia force due to fluid-flow effect. To evaluate the both terms, we use Jacob number *Ja*. Jacob number can distinguish whether heat transfer or inertia-force controls dominantly the condensation on the phase interface of the system. The Jacob number *Ja* is defined as follows [9],

$$Ja = Cp_l \rho_l (T_h - T_w)/L\rho_v. \quad (2)$$

Figure 9 contains Jacob number and interface temperature T_s for both media under both treatments. Jacob number for treatments-I are $Ja \le 46.99$, whereas for treatment-II are $Ja \le 19.23$. The higher *Ja* on the treatments-I are caused by higher temperature difference $(T_h - T_w)$ of that treatments. However, as also mentioned in the figure, all of the *Ja* of the both treatments are less than 100. It gives information that heat transfer, in this same V_c, dominates to control condensation on the interface rather than inertia.

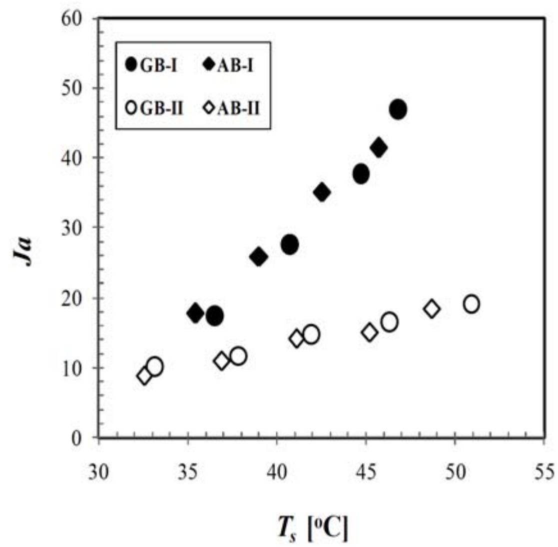

Figure 9. Jacob number on condensation.

3.2.1. Effect of thermal conductivity

Corresponding to the important role of heat transfer on the condensation in the previous discuss, effects of thermal conductivity on the heat transfer of the condensation, further, is discussed in this stage. On the both treatments, condensation number H_L of alumina media is higher than that of glass, shown in Figure 10. The H_L is defined as [7]

$$H_L = k_{eff}\,(T_h - T_s)/\mu_L L, \tag{3}$$

where

$$k_{eff} = k'k''z/[k''\delta + k'(1 - \delta)]. \tag{4}$$

Based on equations (3) and (4), it can be explained that for the same temperature difference $(T_h - T_s)$ and latent heat of condensation L, the H_L is depended on effective thermal conductivity k_{eff} of the porous bed layer filled by condensate. This effective conductivity depends on the jointly effective thermal conductivity (of particles and gas/liquid in the voids) and the condensate thickness δ. Thermal conductivity of the alumina particles is larger than that of the glass particles and even the liquid condensate. Therefore, it can be understood why the H_L of the alumina in both treatments are higher than the glass media.

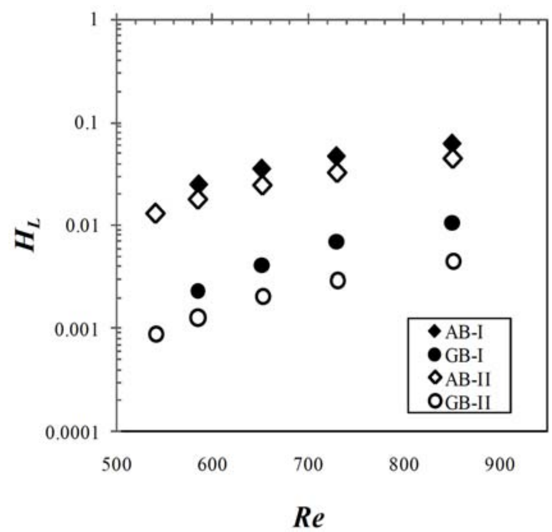

Figure 10. Relation between H_L and *Re*.

If compared with Figure 2, there is interesting note on point series of AB-II and GB-I shown in Figure 10. Positions of the both series are inverse to each other. For the δ, GB-I series is upper than that AB-II (shown in Figure 2), whereas for H_L, AB-II series is on upper. We can argue that the phenomena caused by the ambient treatments have higher effects than that by the thermal conductivity on the overall product of condensate. From this case, it can be now distinguished that the overall condensate product is obtained from condensation on the interface and on the walls. On the interface, heat transfer due to thermal conductivity of particles media has a significant influence on the condensation, whereas ambient treatments have a strong effect on the wall. Practically, based on the overall condensate product in the same humid air temperature T_h, it can be stated that thermal conductivity of particles has significant effect on the condensation (Figure 8), however ambient temperature has higher significant effect than the thermal conductivity.

In this study, diameter of both porous media particle is the same, i.e., 1 mm. Therefore, any parameters respecting to the diameter can be omitted. Hence, the influence of the thermal conductivity of the media can then be considered to represent the effect of the both media, that is, alumina balls and glass beads.

Hereafter, laminar flow regime of the mixture flow is known by Reynolds number *Re* less than 2300, as shown in Figure 10. From the figure, it can be mentioned that *Re* has almost linear relation with the H_L.

3.2.2. Effect of mixture flow

Refers to the influence of the inertia force in this study, this term discusses them in detail based on both analytical and experimental views. In the previous discussion, it is known that condensation occurs due to the existence of heat flux flow in both the walls and upper face, or interface, of the porous bed. On the interface, sum of the heat flux consumed by condensed vapor q_j and the heat flux supplied to the interface q_c gives the total heat-flux removed through the interface Q_w. They can be expressed with the relation

$$Q_w = q_c + q_j. \quad (5)$$

In the case of absent porous media, the heat fluxes ratio on the horizontal base related to diffusion parameter and thermal parameter on condensation was analytically proposed [3] as

$$Q_w / q_c = 1 + Le^n b_{ld} Ku, \quad (6)$$

where *Le* is Lewis number, b_{ld} is diffusion parameter, and *Ku* is Kutaleladze number or subcooling parameter. Based on equation (6), heat flux flow on the condensation regarding phase interchange and interrelation heat and mass transfer can be shown that influence of the mixture flow is considerably small. Therefore, in this current study, it can be stated that effects of the moist air flow, represented by Reynolds number *Re*, is considerably small. It is based on both the evaluation of Jacob number *Ja* of this current study and the heat flux of analytical study in [3]. The analytical study also explained explicitly that due to the effect of Reynolds number on the heat flux was small, therefore, equation (6) can be applied to both laminar, with $n = 0.6$, and turbulent, with $n = 0.66$, flow mixture regime. To the both $n = 0.6$ and $n = 0.66$ values, they also confirm that the small influence of the flow on this condensation dominated by heat transfer.

The inertia force is generated by the mixture flow. In this study, the mixture flow can be represented by Reynolds number *Re* of the flow. For this experiment, the *Re* range are 539.38 to 850.77, as shown in Figure 10. The range means that all of the condensation lies on the same regime consideration, that is, laminar. The narrow enough range of the *Re* can be understood that, indeed, it is caused by the compressed air that is supplied to the humidifier is on the same capacity, i.e., 20 L/minute. Therefore, it can be stated that the narrow *Re* is due to the difference velocity of the mixture flow is only generated by the pressure of the humidifier vessel occurred by varied temperature of humid air. The small role of this mixture flow are also depicted in Figure 10, where condensation number H_L for both alumina ball (AB) and glass beads (GB) media compromise linear function of *Re*.

3.3. Heat fluxes on the interface

Effective condensation, where it results the highest condensate thickness, has been known. However, the most efficient condensation one is yet unclear. Therefore, this term is intended to discuss the efficient condensation based on heat flux ratio on the process. Based on equation (6), ratio of heat flux consumed by condensed vapor q_j to overall heat flux removed through interface Q_w, can be expressed analytically as follows:

$$q_j/Q_w = Le^n b_{ld} Ku/(1 + Le^n b_{ld} Ku) \quad (7)$$

with the experimental result of this study, that is, $q_j/Q_w{}^{\#}$, the equation gives a base line ratio of

$$q_j/Q_w{}^{*} = q_j/Q_w{}^{\#}/q_j/Q_w \quad (8)$$

as shown in Figure 11. The linear line with the range of 30-55°C temperature on upper face of porous bed is under 99%RH of moist-air mixture or humid-air. Depicted in the figure, presence of porous media generally suppresses the $q_j/Q_w{}^{*}$ from the analytical base line.

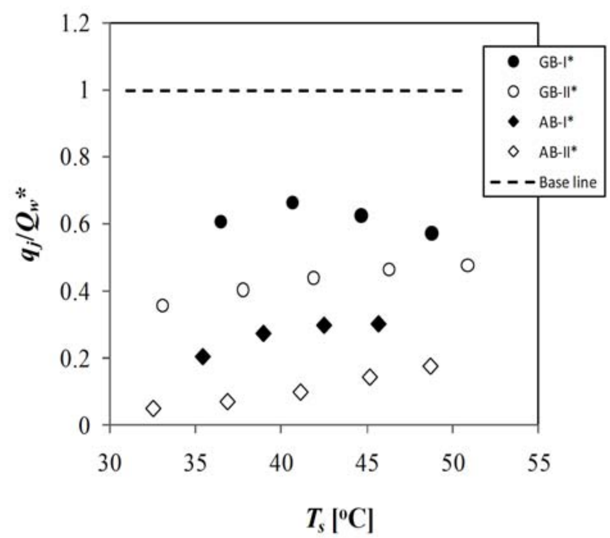

Figure 11. Ratio of heat fluxes through the interface.

3.3.1. Effect of removed heat flux on interface

Compared with the base line, in the treatment-II, where condensation takes place only on the surface of media, $q_j/Q_w{}^{*}$ point series of alumina balls media (AB-II*) occupies on lower position than that glass beads media (GB-II*) and on the lowest position than the others. It can be explained that thermal conductivity k of the media plays the role in this case. In the same q_j, the highest heat flux removed on the interface Q_w makes the lowest series. Due to alumina particles having the highest thermal conductivity, i.e., 18.84 W/mK (see Table 1) than glass particles and the mixture, so the heat flux supplied to media (also means heat flux loss through media) from humid air q_c is the highest as well. The highest q_c contributes to the lowest Q_w, and consequently, it decreases the $q_j/Q_w{}^*$ line of alumina media. Hence, it can be understood why the position of glass beads on GB-II series is between the AB and the base line.

For the GB with thermal conductivity of glass particle is 1.035 W/mK (see Table 1), it is understandable that the position of $q_j/Q_w{}^*$ series is upper than the alumina media (AB-II*) series. It is due to the smaller of the k_{eff} decreases the q_c, and consequently, the Q_w as well. For the base line, the porous media bed is replaced by mixture. Therefore, the thermal conductivity of them refers to the thermal conductivity of air k_{air}, i.e., ~ 0.024 W/mK, and of water vapor k_{vapor}, i.e., ~ 0.016 W/mK, respectively. This smallest thermal conductivity of the mixture makes the smallest Q_w, and consequently, it locates the base line on the top position.

For treatment-I, subsequently, series of the both AB-I* and GB-I* are higher than that AB-II* and GB-II*, respectively. Based on equation (4), it can be explained that in the combination of porous bed with inserted liquid condensate in their void, increasing of the δ decreases the effective conductivity of the combination. Hence, it decreases q_c, or elevates the $q_j/Q_w{}^*$ on the respective media.

3.3.2. Effect of consumed heat flux on condensed vapor

In the case of same heat flux loss through media Q_w, higher q_j, i.e., it means higher produced condensate, causes higher $q_j/Q_w{}^*$ or condensation "efficiency" line. As shown in Figure 11, it can be stated that treatment-I on glass media (GB-I*) results the highest efficiency line than that the other media and the other treatments. This figure also shows that the highest ratio, means the most efficient condensation in this test, is on the glass media at $q_j/Q_w{}^* = 0.663$ on the interface temperature $T_s = 40.7\,°C$ under the treatment-I at humidified air temperature $T_h = 45\,°C$.

4. Conclusion

Based on the discussion, the main results of this study can be concluded as follows:

1. Based on the Jacob number Ja evaluation, the condensation is dominantly controlled by the heat transfer on the system, whereas the inertia force plays a minor effect on the process.
2. Together with the vapor concentration V_c, thermal conductivity of particles k and effective thermal conductivity of pack bed of media k_{eff}, the ambient treatment-I plays a key role on the condensate thickness.
3. Based on the heat flux ratio $q_j/Q_w{}^*$, glass beads media under treatment-I (GB-I) situates the highest efficiency than that the other media and treatment.

Acknowledgment

We wish to thank Mr. Maizul Majeed, and special for Mr. Takahiro Taguma for their valuable help in the experiments.

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