

Experimental Studies of Heat-Transfer Behavior at a Casting/Water-Cooled-Mold Interface and Solution of the Heat-Transfer Coefficient

Y D Zeng , F Wang

College of Materials Science and Engineering, Inner Mongolia University of Technology, Huhehaote, 010051, China
E-mail: zyidan@sina.com

Abstract. In this paper, we propose an experimental model for forming an air gap at the casting/mold interface during the solidification process of the casting, with the size and formation time of the air gap able to be precisely and manually controlled. Based on this model, experiments of gravity casting were performed, and on the basis of the measured temperatures at different locations inside the casting and the mold, the inverse analysis method of heat transfer was applied to solve for the heat-transfer coefficient at the casting/mold interface during the solidification process. Furthermore, the impacts of the width and formation time of the air gap on the interface heat-transfer coefficient (IHTC) were analyzed. The results indicate that the experimental model succeeds in forming an air gap having a certain width at any moment during solidification of the casting, thus allowing us to conveniently and accurately study the impact of the air gap on IHTC using the model. In addition, the casting/mold IHTC is found to first rapidly decrease as the air gap forms and then slowly decrease as the solidification process continues. Moreover, as the width of the air gap and the formation time of the air gap increase, the IHTC decreases.

1. Introduction

A water-cooled mold has a very strong cooling capability, and is often used in cast molding of non-ferrous-metal casting. Generally speaking, if the heat-transfer capability of the casting is strong, then the cooling rate of the casting is high, the obtained casting microstructure is fine, and the corresponding mechanical performance is high. However, during the solidification process of the casting, due to casting shrinkage and casting expansion, the casting and mold no longer closely contact each other and an air gap is formed between them. The air gap inhibits the heat exchange between the casting and the water-cooled mold, which greatly lowers the original cooling ability of the water-cooled mold. As a result, the expected cooling rate can hardly be achieved. Thus, the impact of the air gap on heat exchange at the interface has drawn intensive and wide attention from researchers.

Often, the heat transfer at the casting/mold interface is described using the IHTC. The theoretical studies have already confirmed that once an air gap has formed at the interface, the IHTC will be changed dramatically[1]. Approaches of studying the interface air gap and its impact on heat transfer mainly include the actual measurement method and the heat-transfer coefficient inverse analysis method. Early-stage investigations were focused primarily on actual measurement of the size of the air gap at the interface[2–4] but as it is affected by various factors, the formation time of the air gap and its width can hardly be measured precisely, and the rules indicating how the air gap influences heat transfer cannot be obtained. Given the fact that insurmountable issues existed in the experimental

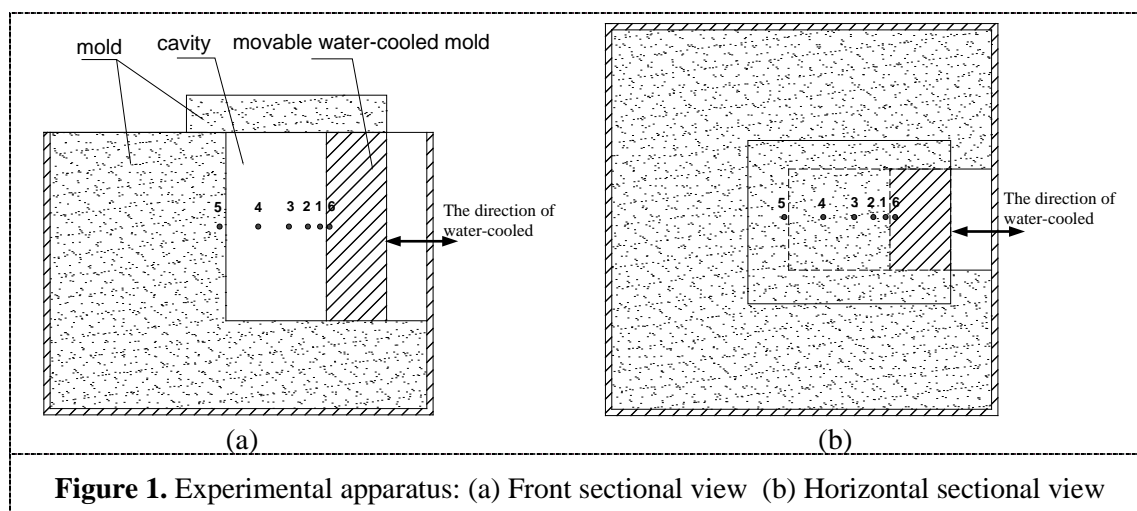


measurements, subsequent research focused more on using the nonlinear estimation method to obtain the IHTC between the casting and mold[4–8]. However, because the impact of the air gap was not taken into consideration, the deviation of the result could be large. Current studies are focused on establishing mathematical models with higher accuracy in which the air gap is taken into consideration[9–12]. It can be seen that no matter whether the actual measurement method or the heat-transfer coefficient inverse analysis method is used, both methods are based on the accurate measurement data of the size and formation time of the air gap. The challenge of the research lies in the fact that the air gap formation time and the size of the air gap still cannot be accurately measured. Directed towards the above issues, in this paper we first propose a new experimental model that is able to accurately and manually control the size and the formation time of the air gap at the interface during the solidification process, thus overcoming the difficulties of direct measurement. Further, using this model, pure aluminum was adopted as the experimental material to perform casting experiments, and the cooling curves of the casting under different conditions of the size and formation time of the air gap were measured, and on this basis, the influence of the air gap on the heat transfer coefficient was analyzed.

2. Experimental design

2.1. Experimental Model

As shown in Figure 1, the experimental model is a combined casting with the inner chamber being rectangular and the top, bottom, and three sidewalls made of an insulating material. Additionally, the rest of the sidewall of the casting is a metallic water-cooled mold. There is a water channel inside the water-cooled mold, which is cooled by the circulating water. The water-cooled mold may move with respect to the other five casting walls. When the metallic liquid is poured into the casting, the water-cooled mold moves in a direction toward the casting to closely contact the casting, such that no air gap is formed. When the solidification thickness reaches a preset value, the movement of the water-cooled mold is reversed to form an interface air gap. Thus, the size and formation time of the air gap can be precisely controlled. A pressure sensor is installed on the water-cooled puncher, which can accurately capture the contact status between the water-cooled mold and the casting.



2.2. Experimental Strategy

To study the impact of the air gap on the IHTC, two factors—the width of the air gap and its formation time—are used as the controlling factors to carry out the experiments, and, in particular, the formation time of the air gap is controlled by the thickness of the solidification layer, which is converted into time. The width of the air gap is configured to be 0.5, 1, and 2 mm, and the formation time of the air gap is configured to be the time when the solidification thickness of the casting reaches 30 and 50 mm..

2.3. Temperature Measurement and Formation of Air Gap

The temperature measurement points of the thermocouple are distributed as shown in Figure 1, where points 1–4 show a distance of 5, 10, 30, and 50 mm, respectively, to the casting/water-cooled-mold interface. Furthermore, point 6 measures the temperature of the water-cooled-mold wall, which is inside the water-cooled-mold wall and displays a distance of 1 mm towards its surface. Point 5 measures the temperature of the casting, which is 5 mm from the surface of the casting. The K-type thermocouple is applied to measure the temperature; the diameter of the thermocouple wire is 0.1 mm. To have a faster response to the temperature, the exposed thermocouple may be applied. Moreover, data collection is realized by utilizing a data acquisition module (DAQ-USB-2401, Omega Engineering, USA), in which the sampling frequency is 100Hz. The temperature variance at each temperature measurement point is recorded during the experimental process.

The air-gap-controlling method refers to the fact that when the metallic liquid is poured into the casting, the water-cooled mold moves in a direction toward the casting, thus allowing the water-cooled mold to closely contact the casting to avoid any air gap. When the formation time of the air gap reaches a preset value, the movement of the water-cooled mold is reversed to form an interface air gap with a preset width.

2.4. Experimental Material

The material of the experimental casting is commercially pure aluminum, the casting temperature is controlled between 780 and 790°C, and top casting is applied. For the casting and the mold material, their thermophysical parameters, the solid fraction, etc. vary as the temperature varies, which may be calculated using PROCAST software

3. Solution of the heat-transfer coefficient

The interface heat-transfer coefficient is calculated using the nonlinear estimation method proposed by Beck[13] where the minimization of $F(h)$ is applied as the determination base, as shown in the equation (1):

$$F(h) = \sum_{j=1}^{K_1} \sum_{i=0}^{K_2} (T_{j,i} - \theta_{j,i})^2 \quad (1)$$

where $T_{j,i}$ and $\theta_{j,i}$ are the simulated temperature and the experimental measurement temperature, respectively, of the measurement point j during the time period i ; K_1 and K_2 are the total number of temperature measurement points and the total number of time periods, respectively; and h is the IHTC. By mathematical deduction, the IHTC is eventually obtained.

4. Experimental results and analysis

4.1. Actual Measurement Curves

Figure 2 illustrates the temperature variance curves of measurement points 1–6 when the width of the air gap is 0, 0.5, 1 and 2 mm., respectively. It is found that when the air gap width is 0 mm [Fig. 2(a)], the curves of temperature measurement points 1–4 inside the casting do not exhibit the phenomenon that the temperature first decreases and then increases, and the decreasing rate of the temperature at each point is relatively high. When the the air gap is formed [Fig. 2(b,c,d)], the curves of temperature measurement points 1–4 inside the casting first decrease rapidly and then increases, and the rate of temperature decrease of each point is significantly lower than that in Fig. 2(a). This indicates that the heat transfer between the casting/water-cooled-mold interface before formation of the air gap occurs very quickly, and the temperature at the casting wall decreases rapidly. However, after the air gap is formed, the heat transfer between the casting/water-cooled-mold interface is inhibited, and the heat-transfer rate decreases, which leads to the increase of the temperature at the casting surface. Thus, the formation of the air gap has a great impact on the interface heat transfer.

As can be seen from the [Fig. 2(b,c,d)], the wider the air gap width, the higher the temperature increase at the casting surface. This indicates that an increase in the width of the air gap results in greater heat-transfer resistance of the casting/mold interface. The width of the air gap in castings is

often smaller than 3 mm, and as a result the air gap is a factor that must be considered during study of the interface heat transfer and actual casting solidification process.

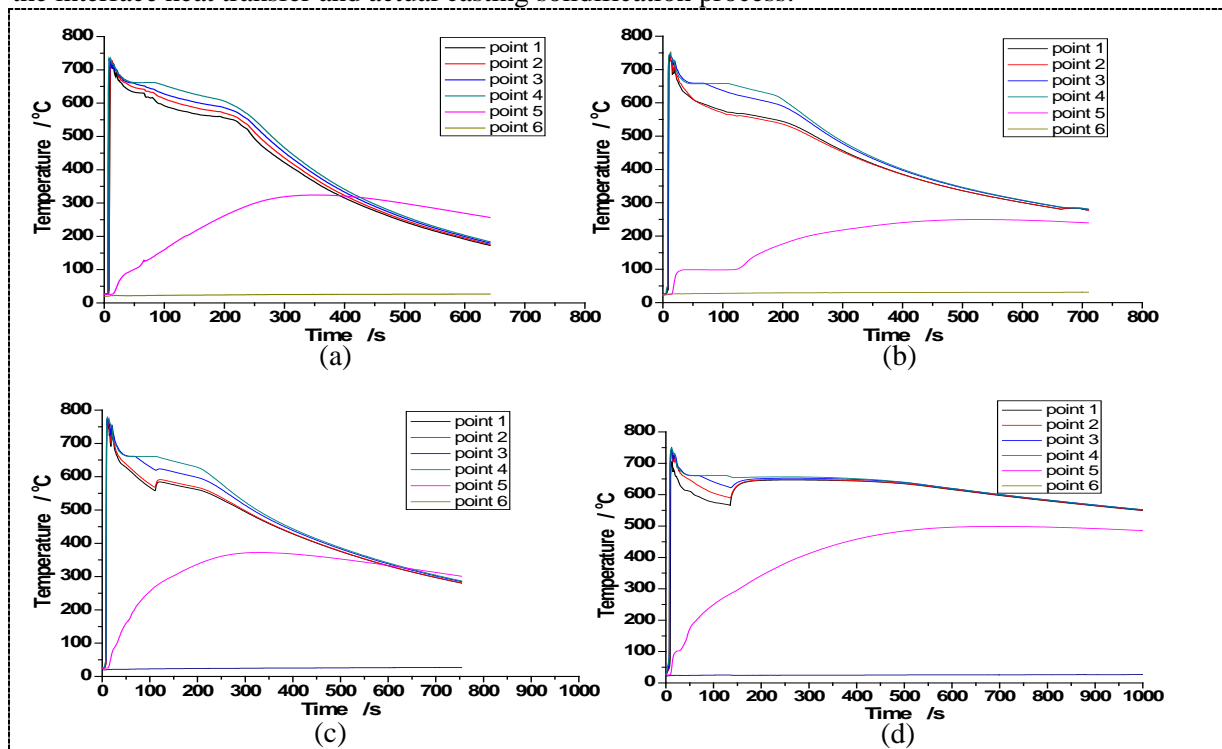


Figure 2. Measured temperature curves at different air gap widths.

(a) air gap width: 0mm (b) air gap width: 0.5mm (c) air gap width: 1mm (d) air gap width: 2mm

Figure 3 presents the temperature variance curves of each measurement point when the formation time of the air gap increases from 90 to 140 s and the width of the air gap is established to be 1 mm. The temperature curves all indicate that the temperature first decreases rapidly, then increases, and, later, decreases further. As the formation time of the air gap increases, the rising point of the temperature is postponed correspondingly. Specifically, when the formation time of the air gap is 90 s, the temperature at measurement point 1 increases by 18°C, and when the formation time of the air gap is 140 s, the temperature at measurement point 1 increases by 12°C. Similar rules are found for the temperature variance measured at point 2; however, with a decreased amplitude of the increase in the temperature, and, furthermore, the temperatures at the same measurement point are different. This is

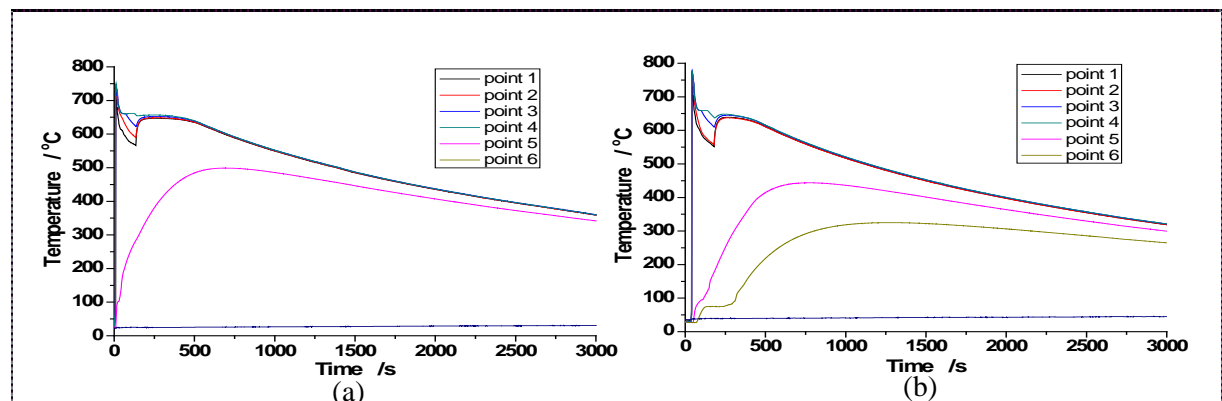


Figure 3 Measured temperature curves at different durations of air gap formation
(a) duration of air gap formation :90s (b) duration of air gap formation :140s

because when the formation time of the air gap varies, the time that the interface contacts the casting varies, and the heat-transfer condition changes correspondingly, which results in the change of the cooling rate of the casting. Clearly, the formation time of the air gap influences the interface heat transfer.

4.2. Solution of Interface Heat-Transfer Coefficient

Taking Eq. (1), the PROCAST software is applied to calculate the IHTC under conditions of different air gap widths and air gap formation times, and the results are shown in Figs. 4–5.

Figure 4 shows the calculation results of the heat-transfer coefficients when the air gap width is 0, 0.5, 1, and 2 mm, and the formation time of the air gap is 90 s. As the solidification time increases, the aforementioned heat-transfer coefficients all show a decreasing trend. The heat-transfer coefficient corresponding to an air gap width of 0 mm is far greater than that of other three situations. When the air gap width is 0.5 mm, the decrease of the heat-transfer coefficient is relatively slow, and when the air gap width is 2 mm, the heat-transfer coefficient decreases rapidly [Fig. 4(d)]. Under the condition that an air gap exists, by comparing the heat-transfer coefficients it can be found that when the air gap width increases, the heat-transfer coefficient decreases. Furthermore, the greater the air gap width, the faster the decrease in the heat-transfer coefficient. Under the present experimental conditions, the cooling time is 90 s, the air gap width increases from 0.5 to 2 mm, and the heat-transfer coefficient decreases from 559 to 128 $\text{W/m}^2\cdot\text{K}$. As the cooling time increases, the difference between heat-transfer coefficients for different air gap widths decreases.

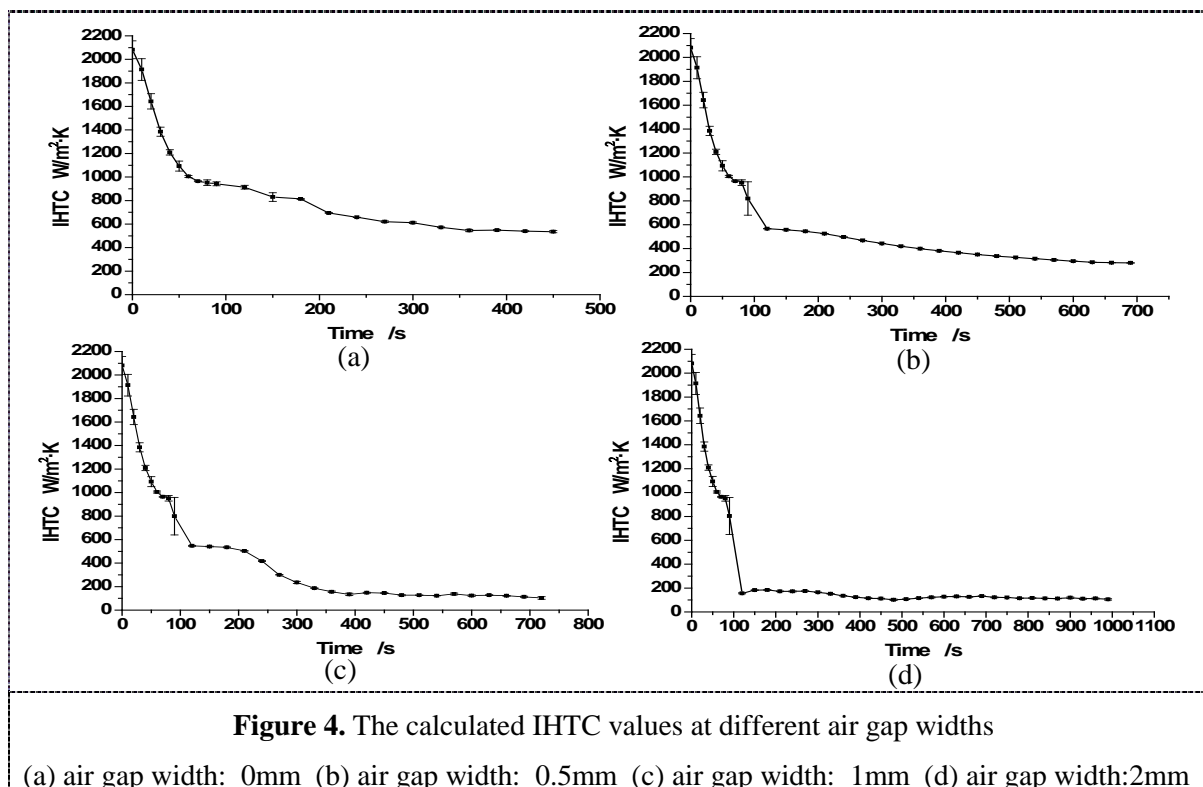


Figure 5 shows the calculation results of the heat-transfer coefficient when the air gap width is 2 mm, and the formation time is 90 and 140 s. As the air gap formation time increases, the interface heat-transfer coefficient decreases. When the cooling time is 300 s, the heat-transfer coefficients of the above two formation times are 156 and 123 $\text{W/m}^2\cdot\text{K}$, respectively. This is because when the air gap formation time increases, the contact time between the casting and the water-cooled mold elongates, and the surface temperature of the casting thus decreases rapidly. By then, the air gap is formed, and the radiation effect of the casting interface is weakened. Accordingly, the heat-transfer coefficient becomes relatively low. As the cooling time increases, the difference between heat-transfer

coefficients calculated using different air gap formation times decreases. The heat-transfer coefficients corresponding to different air gap formation times basically all show the phenomenon that the IHTC first decreases rapidly and then decreases slowly.

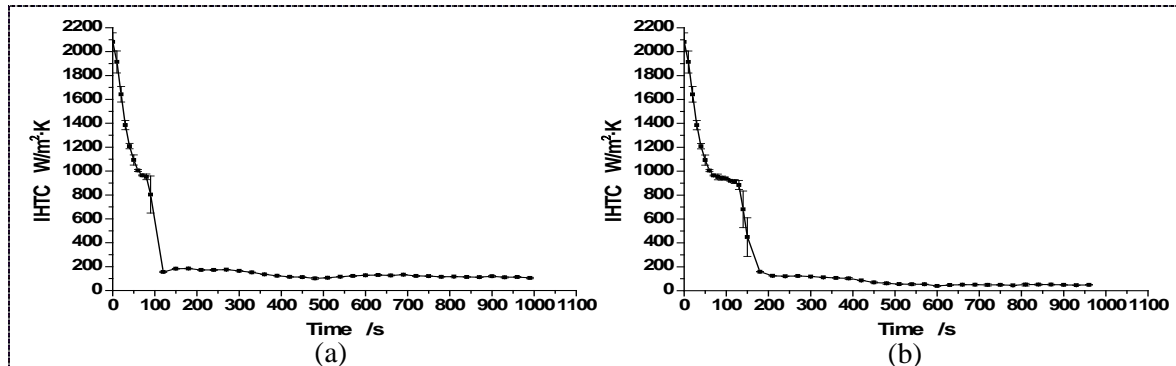


Figure 5. The calculated IHTC values at different durations of air gap formation
(a) duration of air gap formation :90s (b) duration of air gap formation :140s

5. Conclusions

The experimental model for precisely controlling the size and formation time of the air gap at a casting/mold interface is designed, and is applied for studies of casting experiments and of the heat-transfer coefficient. The experimental results indicate that the usage of such a model yields a more accurate and a more effective understanding of the impact of the size and the formation time of the model on the heat-transfer coefficient.

The temperature variance curves of the experimental casting are measured, and the heat-transfer coefficients are obtained via inverse analysis. After the air gap is formed, the temperature inside the casting displays an increasing phenomenon. The wider the air gap, the higher the temperature increases. The calculation results of the heat-transfer coefficient indicate that the impact of the air gap on the heat-transfer coefficient is significant. In the present experiments, by comparing a situation where no air gap is formed and another situation where a 0.5mm air gap is formed, the maximum heat-transfer coefficient decreases from 2157 to 559 W/m²·K. Moreover, the heat-transfer coefficient decreases as the air gap width and formation time increase.

6. References

- [1] Sarjant R J and Slack M R 1954 *Heat transfer*(Iron and Steel Institute)p 428
- [2] Nishida Y and Matsubara H 1976 *British Foundryman* **69** 274-8
- [3] Li T J, Ren Z M and Ren X F 1990 *Journal of DALIAN University of Technology* **30** 297-300
- [4] Trovant M and Argyropoulos S 2000 *Metal. Trans. B.* **31** 75-86
- [5] Zhu L P and Chen L 2009 *Engineering Journal of Wuhan University* **42** 268-72
- [6] Zhang L Q, Li L X, Zu B W 2010 *Journal of Hunan University(Natural Sciences)* **37** 22-6
- [7] Guo Z P and Xiong S M 2007 *Acta Metallurgica Sinica* **43** 1149-54
- [8] Sahin H M, Kocatepe K, Kayikci R 2006 *Energy conversion and management* **47** 19-34
- [9] Florio B J , Vynnycky M, Mitchell S L and O'Brien S B G 2015 *Applied Mathematics and Computation* **268** 1122-39
- [10] Bertelli F , Faria J D, Goulart P R, Brito C and Cheung N 2016 *Applied Thermal Engineering* **96** 454-62
- [11] Chen L P, Wang Y X, Peng L M, Peng H F and Jiang H Y 2014 *Experimental Thermal and Fluid Science.* **54** 196-203
- [12] Szeliga D, Kubiak K, Ziaja W, Cygan R, Suchy J Sz, Burbelko A, Nowak W J and Sieniawski J 2017 *Experimental Thermal and Fluid Science* **87** 149-60