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Trans. Nonferrous Met. Soc. China 17(2007) 981−986
Transactions of Nonferrous Metals Society of China
www.csu.edu.cn/ysxb/

Performances of electrically heated microgroove vaporizers

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Received 28 August 2006; accepted 22 August 2007

Abstract: An electrically heated microgroove vaporizer was proposed. The vaporizer mainly comprised an outer tube, an inner tube and an electrical heater cartridge. Microgrooves were fabricated on the external surface of the inner tube by micro-cutting method, which formed the flow passage for fluid between the external surface of the inner tube and the internal surface of the outer tube. Experiments related to the temperature rise response of water and the thermal conversion efficiency of vaporizer were done to estimate the influences of microgroove’s direction, feed flow rate and input voltage on the performances of the vaporizer. The results indicate that the microgroove’s direction dominates the vaporizer performance at a lower input voltage. The longitudinal microgroove vaporizer exhibits the best performances for the temperature rise response of water and thermal conversion efficiency of vaporizer. For a moderate input voltage, the microgroove’s direction and the feed flow rate of water together govern the vaporizer performances. The input voltage becomes the key influencing factor when the vaporizer works at a high input voltage, resulting in the similar performances of longitudinal, oblique and latitudinal microgroove vaporizers.

Key words: microgroove; microchannel; vaporizer; electrical heating

1 Introduction

Micro vaporizer has been getting more and more attention due to its compact structure and high heat transfer efficiency. Compared with conventional vaporizers, microchannels or microgrooves fabricated on solid surface by micro-machining methods are generally incorporated into micro vaporizers, which can augment the effective areas of heating surface without excessively increasing flow resistances, offering higher heat and mass transfer rate. Therefore micro vaporizers have been significantly applied in numerous fields, such as chemical industry, mechanical engineering and electric chip cooling[1].

In general, micro vaporizers transfer heat via two ways, that is, thermal contacting of fluids[2−4] and electrical heating. The heat for thermal contacting of fluids could be provided by catalytic combustion. TONKOVICH et al[5−8] developed a compact gasoline vaporizer for portable hydrogen production, which was integrated a microchannel heat exchanger with a catalyzed burner. This vaporizer could process nearly 1 400 L/min of the off-gas from the anode of 50 kW fuel cell.

Compared with thermal contacting of fluids, electrical heating can not only precisely control the temperature of micro vaporizers, but also achieve much higher fluid temperature. BRANDNER et al[9] systematically studied on an electrically heated microstructure heat exchangers. Results show that they have better performances for heating velocity, heat exchange efficiency and temperature control than those of conventional heating system. The ratio of thermal power to electrical power can reach 93%. HENNING et al[10] found that the geometries of microchannels could greatly influence the performances of electrically powered micro-heat exchangers.

Microchannels are generally fabricated by micro-machining methods such as wet and dry Silicon [11], LIGA[12] and wet chemical etching[13−14], while microgrooves are fabricated by micro-cutting method[15]. However, the high cost and low efficiency of micro-machining methods impede the development of microchannel vaporizers. Fabricating microgroove by micro-cutting method becomes the most feasible way to

Foundation item: Project(50436010) supported by the National Natural Science Foundation of China; Project(2005Z2-D0011) supported by the Key Program of Science and Technology of Guanzhou City, China
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realize the rapid continuous production. Moreover, microgrooves have approximate scale with micro-channels. Therefore microgroove vaporizers become a focus of research in this field.

Nowadays few researches related to the electrically heated microgroove vaporizer(EHMV) are available. An electrically heated microgroove vaporizer was proposed in this study, and three kinds of microgrooves with different directions were fabricated on the external surface of the copper tube by micro-cutting method. Experiments related to the temperature rise response of water and the thermal conversion efficiency of vaporizer were done to estimate the influence of microgroove's direction, feed flow rate and input voltage on the performance of the vaporizer.

2 EHMV structure

A compact EHMV was proposed in this study, as shown in Fig.1. It mainly comprised an outer tube, an inner tube and an electrical heater. Micro-cutting method was employed to fabricate microgrooves on the external surface of the inner tube. Flow passage for fluids was formed between the external surface of the inner tube and the internal surface of the outer tube. Silicone oil was filled between the inner tube and the electrical heater cartridge to reduce the contact thermal resistance. The EHMV was 92 mm in length, and 28.8 mm in the outer diameter.

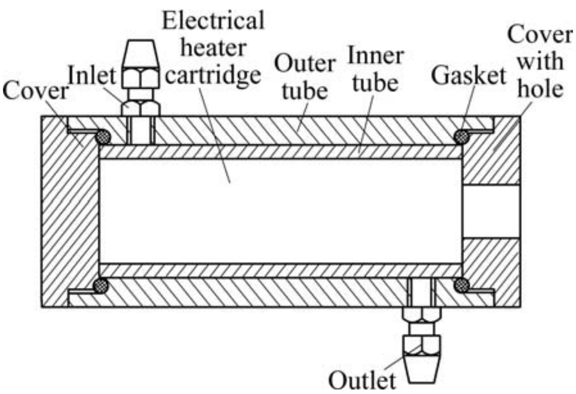


Fig. 1 Schematic diagram of proposed EHMV

Due to its fine heat conductivity, red copper was chosen as the material for the inner tube. Three kinds of microgrooves with different directions were fabricated on the surface of the inner tube, as shown in Fig.2. They were latitudinal, oblique and longitudinal microgrooves, respectively. All the microgrooves were 0.5 mm in width and 0.43 mm in depth. The intervals between the microgrooves with different directions mentioned above were 1, 1.5 and 1.22 mm, respectively.

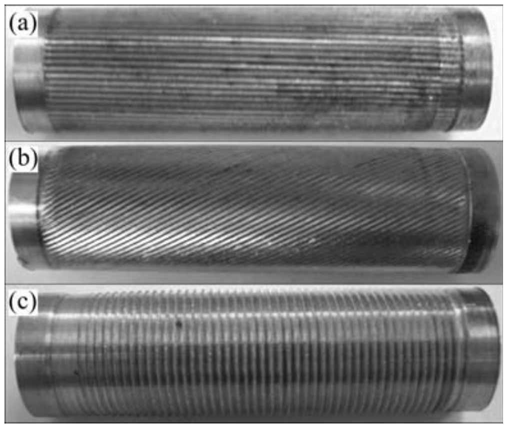


Fig.2 Photographs of three kinds of microgrooves with different directions: (a) Latitudinal microgroove; (b) Oblique microgroove; (c) Longitudinal microgroove

3 Experimental

Fig.3 shows the schematic diagram of experimental set-up for the EHMV. The power of electrical heater cartridge could be continuously adjusted by a voltage regulator when the voltage was 0−250 V. Feed flow rate of fluid was adjusted by a flow controller. The temperatures of the fluid at the outlet were measured by a thermocouple, and then these data were transmitted to a computer via a data acquisition instrument.

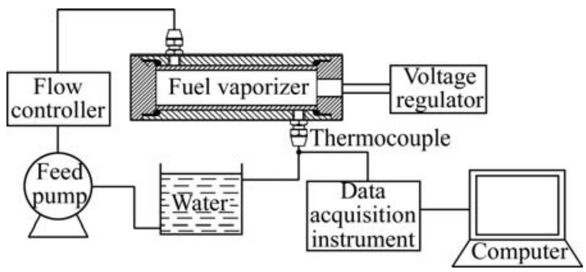


Fig.3 Schematic diagram of experimental set-up for EHMV

In this work, the evaporation of water was chosen as the subject investigated. The water temperatures at the outlet were detected at different feed flow rates of water and input voltages for three kinds of EHMVs. The voltage was preset at four different values, that is, 50, 100, 150 and 200 V. The voltage was firstly set up at a certain value, and then the feed flow rate of water was increased stepwise from 10 mL/min to 100 mL/min, with the increment of 10 mL/min. Meanwhile, the water temperatures at the outlet were recorded every 15 s. Once the feed flow rate reached 100 mL/min, the input voltage was broken off for cooling down the vaporizer. Subsequently the input voltage was changed to another value for next measurement cycle.

The EHMV was not equipped with any isothermal device during experiments. To ensure the uniform experimental condition, the same device was adopted in the whole vaporizer expect the inner tube with microgrooves. It was only needed to change the inner tube for another one after one measurement cycle was finished.

4 Results and discussion

4.1 Temperature rise response of water

One of the key criteria for the evaluation of vaporizer performances is the temperature rise response of water, which refers to the changing rate of water temperatures at the outlet as the time passes. The performance of temperature rise response of water is depended on the amount of heat absorbed by water when flowing in the microgrooves. The more heat in unit interval absorbed by water is, the more quickly the water temperature at the outlet will rise.

The amount of heat absorbed by water could be affected by internal and exterior factors. The internal factors include microgroove's direction and feed flow rate of water. Different directions of microgrooves lead to the change of heat transfer area A, while different feed flow rates result in the change of the heat transfer coefficient K. Considered the internal factors only, the amount of heat Q can be defined as follows:

$$Q=KA\Delta\theta \tag{1}$$

where $\Delta\theta$ is the temperature rise of water.

Exterior factor here refers to the input electrical power P_{in}, which is impacted by the input voltage U and electric resistance R of electrical heater cartridge. From the exterior factor to consider, the amount of heat Q can be defined as follows:

$$Q=(P_{\text{in}}-P_{\text{l}})t=(\frac{U^2}{R}-P_{\text{l}})t \tag{2}$$

where P_{l} is the loss heat power and t is the heating time.

Experiments were investigated on how these two kinds of factors affect the performances of temperature rise response of water in the vaporizers. Fig.4 shows fourteen representative conditions of temperature rise response of water for three kinds of EHMVs at different input voltages and feed flow rates.

For a low input voltage of 50 V, three kinds of EHMVs have closer performances due to comparatively small input electrical power P_{in} and loss heat power P_{l}. At the same time, the microgroove's direction and feed flow rates don't show much influence on the temperature rise response of water.

At a moderate input voltage of 100 V, the microgroove's direction and the feed flow rate of water together govern the performances for the temperature rise response of water. At a small feed flow rate, the longitudinal microgroove vaporizer exhibits better performances than those of the other two kinds. This is because the flow passage formed by the longitudinal microgroove has the largest heat transfer area A, the oblique microgroove has the second, and the latitudinal microgroove has the smallest area. With the increase of feed flow rate, the fouling resistances in the microgrooves decrease, leading to larger heat transfer coefficient K. According to Eqn.(1), the longitudinal microgroove vaporizer presents much more superiority. And the performances of the oblique microgroove vaporizer are slightly better than those of the latitudinal microgroove vaporizer.

Three kinds of EHMVs have similar performance at a comparatively large input voltage of 150 V and lower feed flow rate. Obviously, large amount of heat produced by input electrical power and small volume of water need to exchange heat result in closer performances. But the longitudinal microgroove vaporizer works better than the other two kinds when the feed flow rate surpasses 50 mL/min. This is because the heat transfer coefficient K increases with increasing feed flow rate, and the longitudinal microgroove has the largest heat transfer area. According to Eqn.(1), the heat absorbed per unit time by the longitudinal microgroove vaporizer will be the maximum, leading to the highest water temperature at the outlet.

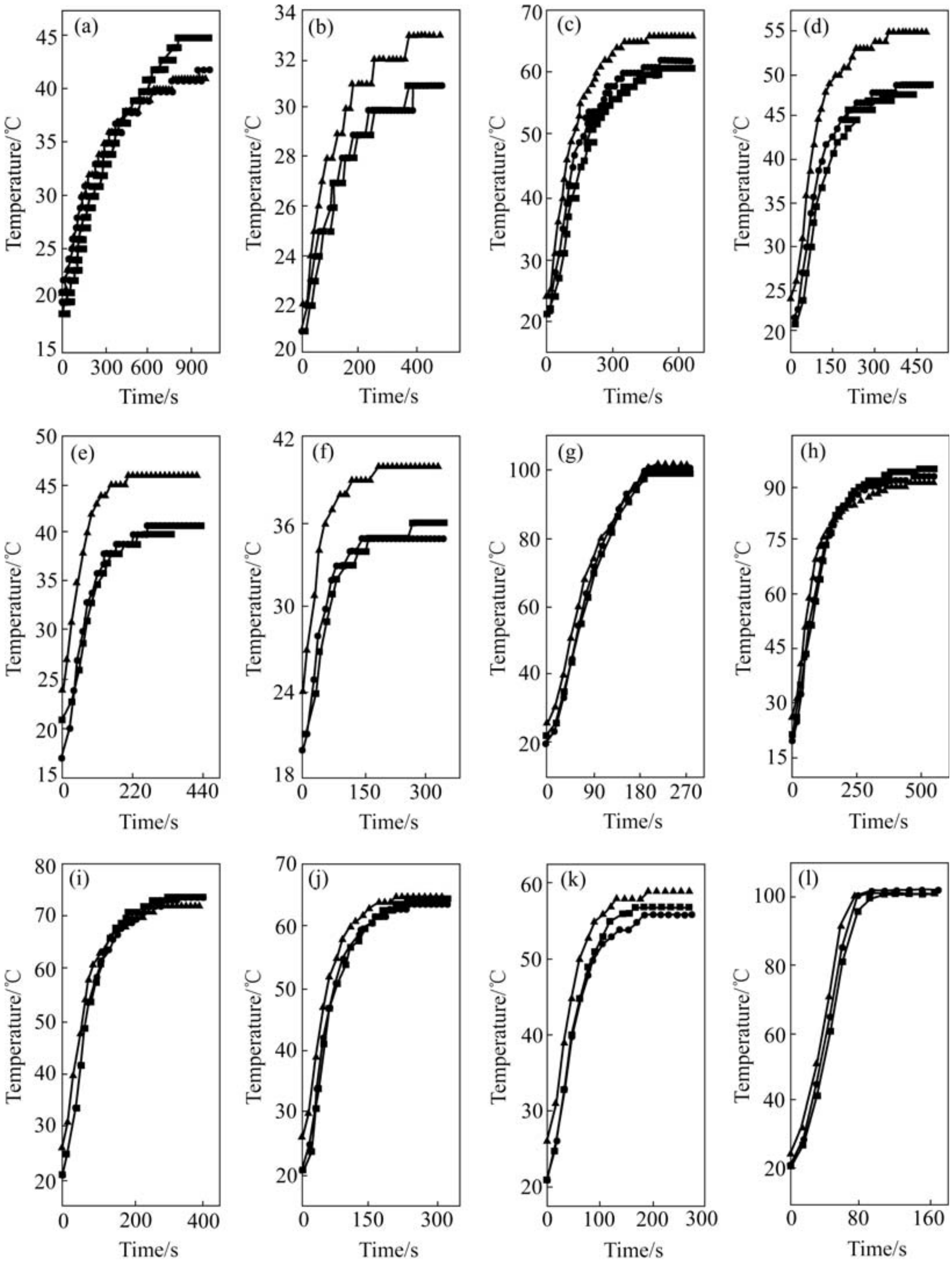
For all three kinds of vaporizers, the curves of the temperature rise response almost match together at a high input voltage of 200 V, which indicates that their performances accord to each other. This is because large input electrical power transfers enough heat for the evaporation of water, and the heat absorbed by water at different microgrooves and feed flow rates of water are almost the same.

4.2 Thermal conversion efficiency of vaporizer

Thermal conversion efficiency η, which is another key criterion for the evaluation of vaporizer performance, is defined as follows:

$$\eta=\frac{P_{\text{w}}}{P_{\text{in}}}=\frac{P_{\text{w}}R}{U^2} \tag{3}$$

where P_{w} is the thermal power absorbed by water, which can be calculated by the water temperature at the inlet and outlet. Supposing the evaporation of water



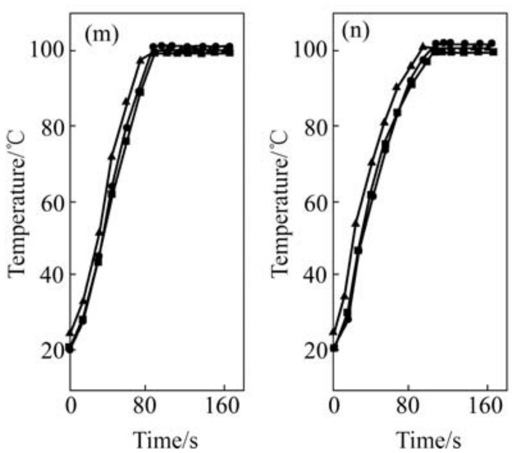


Fig.4 Temperature rise response of water at different input voltages and feed flow rates: (a) 50 V, 10 mL/min; (b) 50 V, 20 mL/min; (c) 100 V, 20 mL/min; (d) 100 V, 30 mL/min; (e) 100 V, 40 mL/min; (f) 100 V, 60 mL/min; (g) 150 V, 20 mL/min; (h) 150 V, 30 mL/min; (i) 150 V, 40 mL/min; (j) 150 V, 50 mL/min; (k) 150 V, 60 mL/min; (l) 200 V, 20 mL/min; (m) 200 V, 30 mL/min; (n) 200 V, 40 mL/min (▲ Longitudinal microgroove vaporizer; ◆ Oblique microgroove vaporizer; ■ Latitudinal microgroove vaporizer)

happens at constant pressure, when the water temperature is below the boiling point, the thermal power absorbed by water should be

$$P_w = G_m c_p(\mathrm{l})(\theta_{out} - \theta_{in}) \tag{4}$$

When the water changes into gas, the absorbed thermal power should be

$$P_w = G_m[c_p(\mathrm{l})(100 - \theta_{in}) + \Delta_{vap}H_m(100\,℃) + c_p(\mathrm{g})(\theta_{out} - 100)] \tag{5}$$

where $c_p(\mathrm{l})$ and $c_p(\mathrm{g})$ are the molar heat capacity for liquid water and vaporous water at constant pressure, respectively; $\Delta_{vap}H_m(100℃)$ is the evaporating enthalpy for water at 100 ℃; θ_{in} and θ_{out} represent water temperature at the inlet and the outlet, respectively; G_m is the mass flow rate.

Fig.5 shows that the thermal conversion efficiency of vaporizer varies with the microgroove's direction at four preset input voltages. Three EHMVs exhibit rather unstable thermal conversion efficiency for lower input voltages of 50 and 100 V. Their efficiencies are all higher than 60% at different feed flow rates. Due to the largest heat transfer area among three kinds of EHMVs, the longitudinal microgroove vaporizer has higher average thermal conversion efficiency than that of the other two kinds.

For higher input voltages of 150 and 200 V, three kinds of EHMVs have approximately same thermal conversion efficiencies and similar variations. The thermal conversion efficiencies are comparatively low for the lower feed flow rate since water evaporates under high input voltage and low feed flow rate, great amount of heat are absorbed by water, leading to low thermal conversion efficiencies. The thermal conversion efficiency is always higher than 90% when the feed flow rate surpasses 50 mL/min.

5 Conclusions

1) The microgroove's direction dominates the vaporizer performance at a lower input voltage. The longitudinal microgroove vaporizer exhibits the best performances for the temperature rise response of water and thermal conversion efficiency of vaporizer.

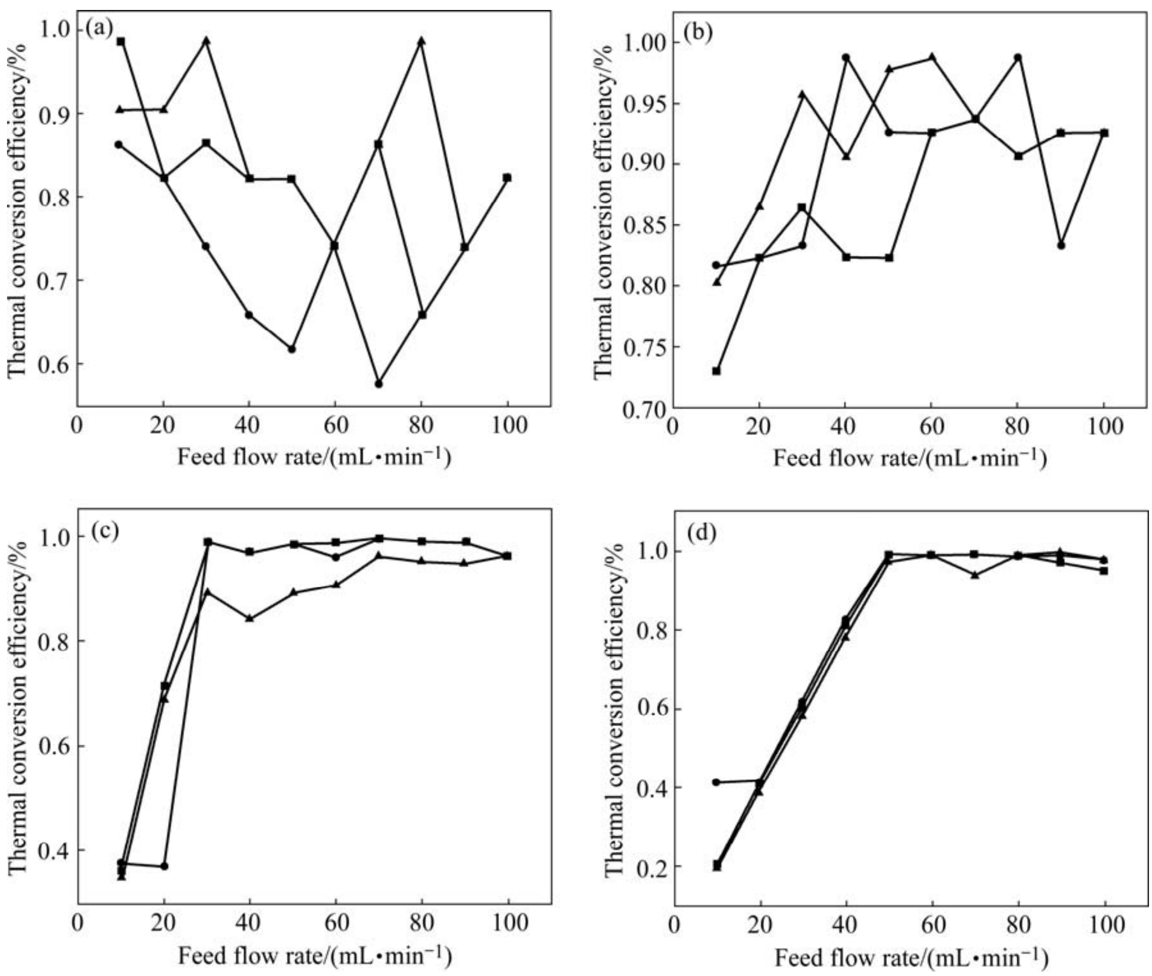


Fig.5 Thermal conversion efficiency of vaporizer at four preset input voltages: (a) 50 V; (b) 100 V; (c) 150 V; (d) 200 V (▲ Longitudinal microgroove vaporizer; ◆ Oblique microgroove vaporizer; ■ Latitudinal microgroove vaporizer)

2) For a moderate input voltage, the microgroove's direction and feed flow rate of water together govern the vaporizer performances. With increasing the feed flow rate, the longitudinal microgroove vaporizer has much better performances for the temperature rise response of water.

3) The input voltage becomes the key influencing factor when the vaporizer works at a high input voltage, resulting in similar performances for the temperature rise response of water and thermal conversion efficiency of these vaporizers.

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(Edited by LI Xiang-qun)