Portable Active Sensors for Human Sweat Rate Monitoring

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***Abstract*— A portable active sweat rate sensor has been developed by integrating a thermo-pneumatic actuator with a humidity measuring chamber, making it possible to switch the skin contact of the humidity chamber for long-term continuous human sweat rate measurement. Previous active sweat rate sensor uses an external pump for measuring the humidity difference in the actively ventilated chamber; thus resulting in the problem of the bulky size with the lack of portability. The portable passive sweat rate sensor uses a humidity chamber for measuring the rate of humidity change in the chamber closed by skin. The passive closed chamber sensor, however, needs a manual ventilation of the humidity chamber after each trial measurement. In this study, we present a portable active sweat rate sensor with an integrated thermo-pneumatic actuator; thus making it possible to switch the skin contact of the humidity chamber for continuous sweat rate measurement. The active sweat rate sensor, fabricated in 41 ± 0.5 mm, 38 ± 0.5 mm, and 25 ± 0.5 mm, respectively, is capable to measure the human sweat rate continuously with the sensitivity of 0.093 (pF/sec)/(g/m^{2}h) and the linearity of 99.2 % in the sweat rate range of 3.7~62.9 g/m^{2}h. The present active sweat rate sensor has demonstrated its potential for human sweat rate monitoring applications, such as human thermal status monitoring jackets and air-conditioning systems based on human sweat.**

Keywords—sweat rate sensor; humidity detection; thermo-pneumatic actuation

I. Introduction

Human thermal status monitoring has been demanded for the development of human-machine interaction systems. For example, human based cognitive air-conditioning system [1] needs to monitor the human thermal comfort for the human-dependent temperature control. Smart jackets [2, 3] which check human conditions also need to monitor the human thermal status for daily checking the physiological conditions of soldiers or athletes. In this respect, continuous measurement of the human signals indicating the human thermal status is highly required.

The major non-invasive human signals indicating human thermal status [4-6] are known as skin temperature, peripheral blood flow, and sweat. Skin temperature is closely related to the core temperature [7, 8] and widely used to evaluate human thermal status. However, skin temperature measurement is unstable due to its high sensitivity to surrounding temperature. To enhance the measurement accuracy, multiple body spots [9] for temperature measurement are required. Peripheral blood flow also reflects the human thermal status [10]. When human feels cold, peripheral blood flow decreases. On the other hand, peripheral blood flow increases when we feel hot. However, peripheral blood flow measurement is unstable to the body movement [11], and compensation process [12] should be followed to increase measurement accuracy. In addition, blood flow is measureable only at the human peripheral spots such as fingertip, ear lobe and toe. Sweat, however, is measurable at the various spots such as wrist, back, chest, neck and etc. Sweat has the term of "sweat rate", which is a quantitative value of human perspiration, and one of the key indicators [13] for human thermal responses. Besides, it has been reported that sweat rate is linear [14] with human core temperature and thermal status. Therefore, we focus on the sweat rate measurement for the human thermal status monitoring applications, such as smart jackets and cognitive air-conditioning systems based on human sweat.

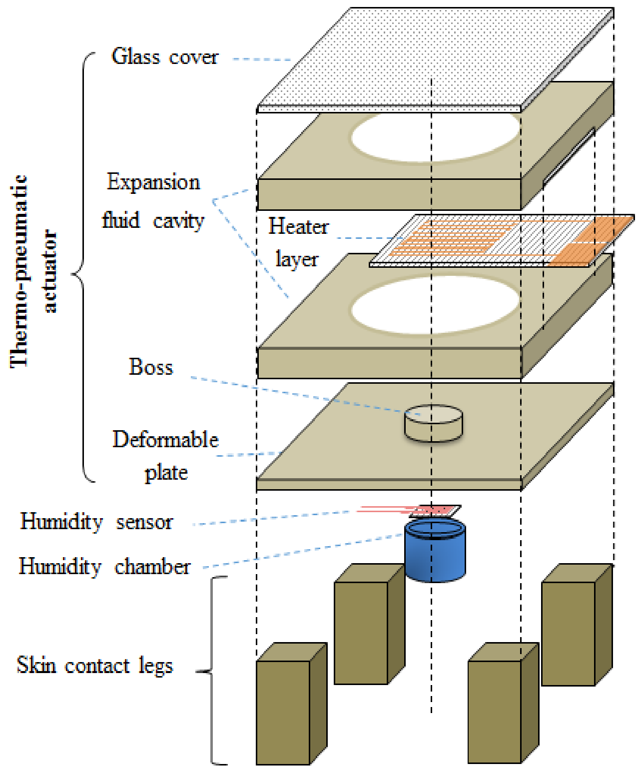

Fig. 1 Layers of the active sweat rate sensor.

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Previous *active* sweat rate sensor [15] uses an external pump for measuring the humidity difference in the actively ventilated chamber; thus resulting in the problem of the bulky size with the lack of portability. The portable *passive* sweat rate sensor [16, 17] uses a humidity chamber for measuring the rate of humidity change in the chamber closed by skin. The passive closed chamber sensor, however, needs a manual ventilation of the humidity chamber after each trial measurement. In this study, we present a portable active sweat rate sensor with an integrated thermo-pneumatic actuator; thus making it possible to switch the skin contact of the humidity chamber for long-term continuous sweat rate measurement.

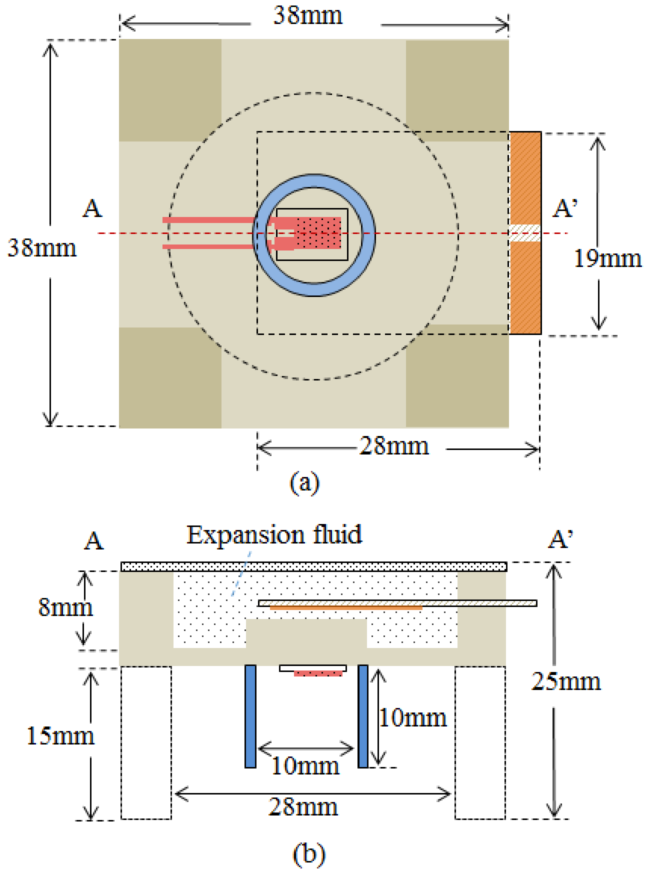

Fig. 2. The active sweat rate sensor: (a) bottom view; (b) cross-sectional view along A-A' in (a).

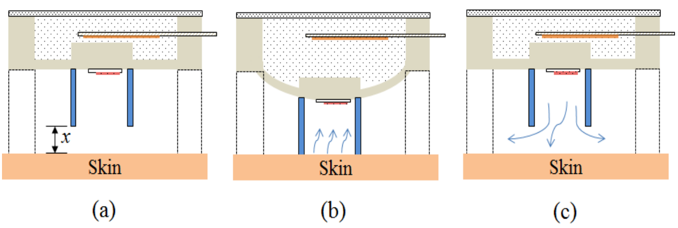

Fig. 3. Operation process of the active sweat rate sensor: (a) initial state with heater off; (b) heater on for skin contact & sweat rate detection; (c) heater off for contact release & chamber recovery.

II. WORKING PRINCIPLE

Fig. 1 shows the overall structure of the active sweat rate sensor. The active sweat rate sensor, designed in the total size of 38 mm × 41 mm × 25 mm (Fig. 2), consists of four skin contact legs, a humidity chamber having a capacitive humidity sensor, and a thermo-pneumatic actuator. The thermo-pneumatic actuator, composed of a deformable plate with boss, an expansion fluid cavity, a heater layer, and a glass cover, preforms the switching motion for sweat ventilation. Fig. 3 describes the switching motion of the active sweat rate sensor. Fig. 3a shows the initial state before the heater on. When the heater is on (Fig. 3b), humidity chamber moves downward direction to be contact with skin for sweat rate detection process. After detection, humidity chamber moves to upward direction (Fig. 3c) by natural cooling for skin contact release and ventilation process. Skin contact for sweat rate detection and contact release for chamber ventilation are repeated by thermo-pneumatic actuator to achieve long-term continuous sweat rate measurement.

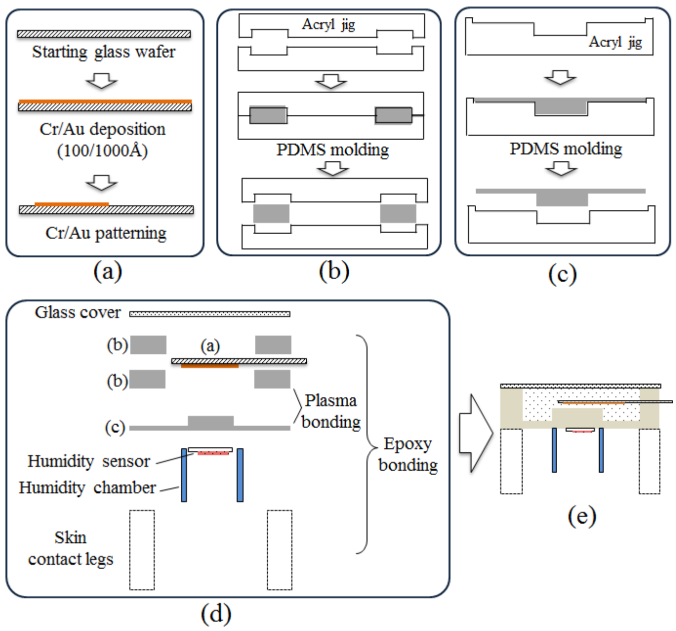

Fig. 4. Fabrication process of the active sweat rate sensor: (a) heater layer; (b) expansion fluid cavity; (c) deformable plate; (d) assembly and bonding process; (e) completed device.

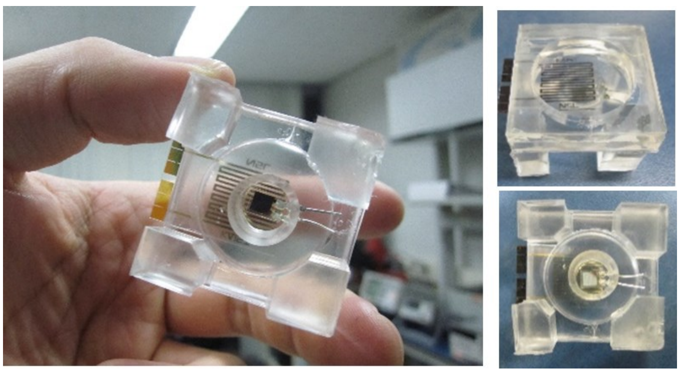

Fig. 5: The fabricated active sweat rate sensor

Thermo-pneumatic actuator is controlled by the heater operation in the expansion fluid cavity. Heater increases the expansion fluid temperature to increase the fluid vapor pressure. On the other way, natural cooling during heater off decreases the fluid vapor pressure. Pressure dependent-deflection of the deformable plate induces the downward or upward actuation of the humidity chamber. For the sweat rate detection, we measure the rising rate of the humidity in the humidity chamber contact with skin. Rate of the humidity changes is the parameter of sweat rate [16]. Humidity is measured by the capacitive humidity sensor placed in the upper position of the humidity chamber.

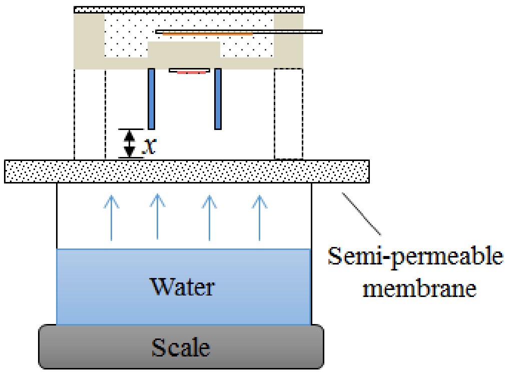

Fig. 6. Experimental setup for characterization of the active sweat rate sensor.

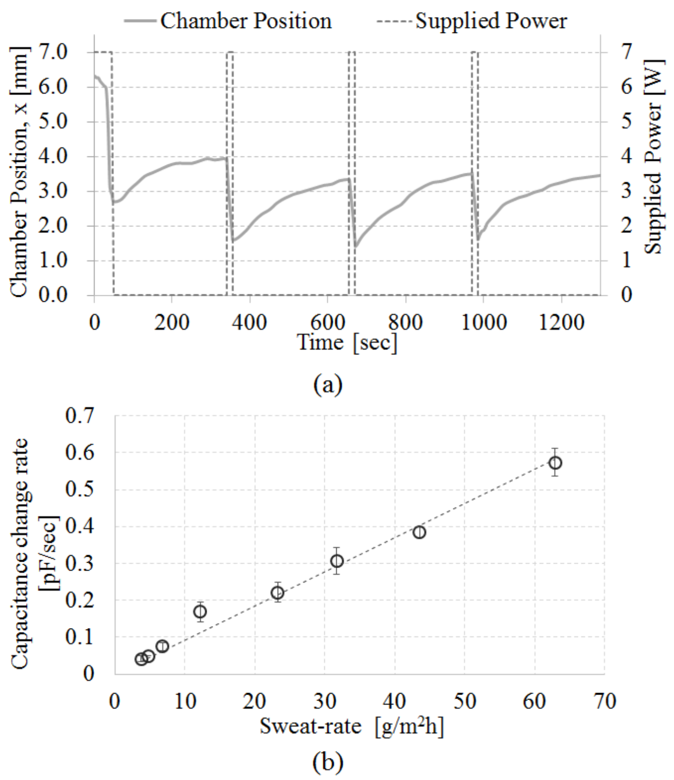

Fig. 7. Characterization of the sweat rate detector: (a) The dynamic responses (solid line) of the humidity chamber position, x of fig.5 for the pulse power supplied to the heater of 7W (dashed line); (b) sweat rate-dependent capacitance change rate.

III. Design and Fabrication

A. Design

Total width of the active sweat rate sensor is determined as 38 mm, considering the average human wrist width of 40~60 mm. Width of the four skin contact legs is 10 mm for stable skin contact and the rest of area determines the diameter of the deformable plate of 28 mm. The size of heater layer is 12 mm × 5 mm, considering the deformable plate diameter, 4 in wafer fabrication yield, and the wiring area of 3 mm × 3 mm. Humidity chamber size is determined by the conventional size of the portable passive device [16]. Capacitive humidity sensor (SY-HC-1, *SAMYOUNG S&C*, Korea) has the size of 7mm × 5 mm which is fully inserted in the humidity chamber.

B. Fabrication Process

Fig. 4 shows the fabrication process of the active sweat rate sensor. Heater layer fabrication (Fig. 4a) was started with 4 in glass wafer. Cr/Au of 100 Å/1000 Å was deposited by evaporation and patterned by photolithography technique. Expansion fluid cavity and skin contact legs were fabricated (Fig. 4b) by the PDMS molding from the acryl mold. Deformable plate was also fabricated (Fig. 4c) by the PDMS molding from the acryl mold but we controlled the PDMS pouring volume to control the thickness of the deformable plate. After the elements fabrication, bonding process (Fig. 4d) was performed by epoxy glue to complete the device fabrication (Fig. 4e). Fig. 5 shows the fabricated active sweat rate sensor having the size of 41 ± 0.5 mm, 38 ± 0.5 mm, and 25 ± 0.5 mm.

IV. Test Methods and Experimental Results

A. Thermo-pneumatic actuation

We characterized the speed of thermo-pneumatic actuator by observing the humidity chamber position with times using video camera. As a result, the switching time of the humidity chamber controlled by the thermo-pneumatic actuator (Fig. 7a) were 20 sec and 5 min in downward and upward direction, respectively, for the switching distance of 2.4 mm at the 7 W pulse power supplied to the heater layer. Initial position of the humidity chamber got lower from 6.1 mm to 3.2 mm but the switching motion of the humidity chamber was stable from the 3rd actuation cycle. Changes in the humidity chamber position is due to the overall rising of the device temperature which prevents the natural cooling for upward actuation.

B. Sweat rate detection

We fabricated the artificial skin generating a controlled sweat rate for calibration process. Fig. 6 shows the experimental setup for the active sweat rate sensor on the artificial skin. Artificial skin is composed of a petri dish filled with water and covered by the semi-permeable membrane (OpSite Flexigrid™, *Smith and Nephew*, UK). Water evaporation through the semi-permeable membrane determines the value of the controlled sweat rate. Evaporation is controlled by the water temperature and the layer number of semi-permeable membrane. Artificial skin can generate 7 points of the controlled sweat rate in the range of 3.76~62.9g/m²h by the water temperature of 25~50 °C, and the layer number of 1, 2 and 4. Sweat rate detection characterization was performed based on the artificial skin. We measured the capacitance of the capacitive humidity sensor with times when the humidity chamber is contact with the artificial skin. Capacitance change rate were measured 3 times for each 7 points of the controlled sweat rate. Fig. 7b shows the sweat rate-dependent capacitance change rate. From the result, the active sweat rate sensor measures the sweat rate at the sensitivity and linearity of 0.093 (pF/sec)/(g/m^{2}h) and 99.2 %, respectively, in the human sweat rate range of 3.7~62.9 g/m^{2}h. Therefore, the active sweat rate sensor presents its potential for the continuous sweat rate measurement.

V. Discussion

The thermo-pneumatic actuator integrated in the active sweat rate sensor can affect the sweat rate detection performance due to its temperature rise. We measured the humidity chamber temperature using thermocouple during the actuation operation. Thermocouple was attached at the upper position of the humidity chamber and overall temperature of the active sweat rate sensor was measured as about 40°C during the thermo-pneumatic actuation. The capacitive humidity sensor in the humidity chamber is insensitive to temperature up to 75°C. Therefore, we concluded that temperature effect for sweat rate detection can be neglected.

The active sweat rate sensor is intended to be attached to the human wrist. When the active sweat rate sensor is attached to the human wrist, initial distance between the skin and the humidity chamber is getting closer due to the skin curved surface and skin elasticity. We observed that the active sweat rate sensor is pressed into the skin about 3 mm. Therefore, thickness of the skin contact legs should be lengthened of about 3 mm to keep distance between the skin and the humidity chamber.

VI. Conclusion

We have designed, fabricated, and characterized the portable active sweat rate sensor developed by integrating a thermo-pneumatic actuator with a humidity measuring chamber, making it possible to switch the skin contact of the humidity chamber for long-term continuous human sweat rate measurement. The active sweat rate sensor fabricated in the width, the height and the thickness of 41 ± 0.5 mm, 38 ± 0.5 mm, and 25 ± 0.5 mm, respectively, capable to measure the human sweat rate continuously with the sensitivity of 0.093 (pF/sec)/(g/m^{2}h) and the linearity of 99.2 % in the sweat rate range of 3.7~62.9 g/m^{2}h. The active sweat rate sensor has demonstrated its potential for human sweat rate monitoring applications, such as human thermal status monitoring smart jackets and cognitive air-conditioning systems based on human sweat.

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