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ORIGINAL PAPER

Analytical Study of Unsteady Boiling Characteristics of Steam Generator

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Abstract

Currently, research on the efficiency of the film heater, which is a surface heating element, is being actively conducted as it is a potential alternative to the sheath heater. However, research on the heat transfer phenomenon and the performance of the film heater is insufficient. In this study, the performance of the sheath heater and the film heater were compared and analyzed, and the heat transfer pattern according to the arrangement of the heating wire was analyzed. To inspect the heat transfer performance, the external heat transfer and internal flow characteristics of the steam generator were determined, and a study on the performance of the steam generator according to each design variable was conducted. The Eulerian multiphase model was used to conduct the multiphase flow analysis, and the wall boiling model was used to conduct the phase change analysis. Among the models analyzed in this study, the model in which the heating wire was arranged along the flow path and the length of the induction was extended by 50% showed the best performance. Compared to the base model, the steam generation time was improved by 33.3% and the steam ejection time was improved by 17%. These times were improved because the heating wire arrangement of the film heater was optimized along the fluid channel. The U-shaped heating wire arrangement enabled a stable steam injection, and in the case of the normal film heater and fluid channel following heater, a large portion of the heating wire was located around the center. Consequently, steam was formed at the center of the housing. We believe that the results of this study can be applied to various fields in consideration of the advantages of the film heater package, free pattern design of printing, and economy.

Keywords Sheath heater · Film heater · Heat transfer · Steam generator · Boiling effect · Computational fluid dynamics

Introduction

Various methods for solid heating have been recently applied to industrial sites and home appliances. Among them, the heating of solids using a heater is widely used, and various types of heaters have been manufactured according to the need for constant temperature maintenance, uniformity, and operating temperature. Among these heaters, the sheath heater, which is a heat source with a built-in coil shape and magnesium oxide, is the most widely used because of its easy installation and high efficiency, and it is used in many fields because it can be manufactured in various shapes depending on the demand of the user [1]. However, there is an inherent risk of electric fire in the power input terminal and lead wires [2, 3]. Furthermore, the heater is large in volume, which increases the size of the product that uses it. To address these disadvantages, film heaters have been recently applied to some products. Compared to the sheath heater,

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the film heater is easier to control. In addition, because it is a thin film on a planar lightwave circuit (PLC), which is a thin-plate type, the size of the product using this type of heater can be reduced significantly. Studies on the multiphase flow model through boiling have been actively conducted, but the analysis model is oversimplified, and therefore the prediction accuracy of the analysis of the actual boiling phenomenon is low. One of the most widely used multiphase models is the two-fluid model using 3D time-averaged multiphase flow conservation equations [4, 5]. Because boiling flow is physically very complex, only 1D analytical studies have been mainly conducted along with experimental-based studies, and recently, many studies on the development of 3D boiling flow models have been reported [6]. In addition, In et al. performed a computational hydrodynamic simulation of the supercooled boiling flow using Kurul's wall boiling model [6, 7]. A standard for the size of the adjacent wall grid was developed by performing a comparative analysis of the computational fluid dynamics (CFD) prediction results and experimental results for the bubble rate and heating surface temperature of the subcooled boiling flow in a vertical tube. Li et al. conducted an analytical study of a spray/boiling-type steam generator using the sheath heater [8]. The research aimed to improve the performance of the spray-type steam generator by addressing the disadvantages of the countertop steam generator, and the researchers also discussed methods to improve various features such as controllability and stability of the spray-boiling steam generator and concentric steam generator [9–12]. The steam generator that is the subject of research in this study mostly uses sheath heaters and is mass-produced. Currently, research on the diversification and efficiency of the film heater material, which is a surface heating element, as the film heater can potentially replace the sheath heater; however, the actual heat transfer mechanism and its performance is not sufficiently studied. Therefore, in this study, the existing sheath heater was compared with a film heater, and the heating performance was compared according to the arrangement of heating elements. In addition, the vaporization performance was compared to derive objective performance values for each model. In this study, the fluid channel length and heater type have been mainly studied to reduce steam generation time and ejection time for fast start and user convenience.

Research Method

Analysis Method

3D Reverse Engineering of Steam Generator

To inspect the internal structure and driving conditions of the steam generator and to obtain design data, a 3D model was developed by reverse engineering a commercial handy steam iron. Figure 1(a) and (b) show the shape of the internal flow path of the handy steam iron and the location of the sheath heater in the final product, respectively.

The operation principle of the steam iron model is as follows: it starts to heat the water when connected to power, and the steam generation begins within 35 s. During the operation, once the steam iron reaches the target temperature of 132 °C, the bimetal switch turns on to stop the heating. If the ejection button is pressed, the steam that has already been formed is ejected. The temperature of the internal flow path of the steam is maintained at approximately 130 °C using a bimetal switch. The heat source is a U-shaped sheath heater that is installed at the bottom of the flow area, and this structure does not facilitate equal heat generation on the steam-generating surface. The actual temperatures were measured, and it was found that the steam temperature of the ejection part was 115 °C, the surface temperature of the ironing part was 105 °C, and the required power was approximately 1370 W. The measured values were used as simulation conditions to conduct heat transfer analysis. In this study, because the flow area and the outer housing where heat transfer proceeds are the main areas of interest, the steam generator electric devices and pumps were not included in the analysis. The schematic of the modeled steam iron is shown in Fig. 2.

Selection of Design Variables

In this study, the length of the flow path, the type of the heat source, and the arrangement of the heat source were selected as design variables. The design variables of each film heater model are summarized in (Table 1) along with those the base sheath heater model (FL10-SH-UA). FL indicates the length of the flow path, FL10 indicates the length of the existing flow path, and FL15 indicates the flow path extended by 150%. SH and FH represent the sheath heater and the film heater, respectively, UA indicates the U-shaped heat wire arrangement, NA indicates the general commercial heating wire arrangement, and FA indicates the flow path that follows the heating wire. The shapes of FL10-FH-UA,

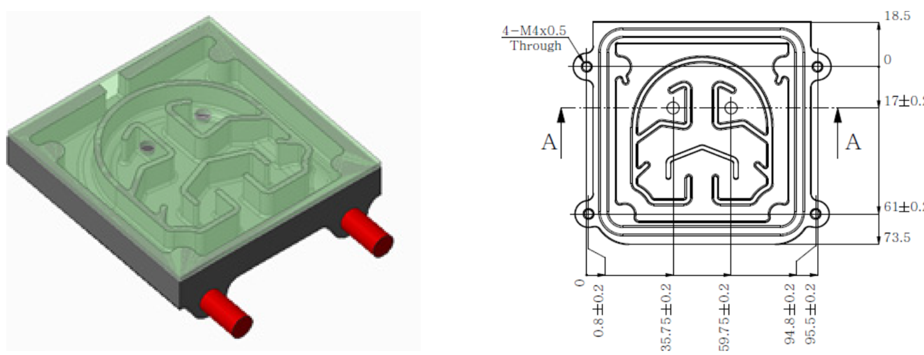
(a) Flow channel (b) Position of sheath heater

Fig. 1 Steam iron model. (**a**) Flow channel. (**b**) Position of sheath heater

FL10-FH-NA, FL15-FH-NA, and FL15-FH-FA were modeled by combining each design variable. The differences between models according to each detailed design variable are shown in Fig. 3.

Analysis Method

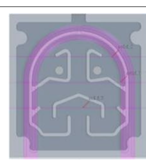
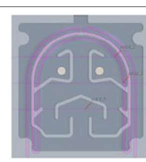
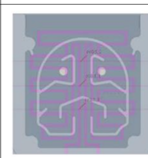
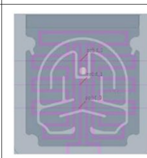
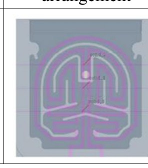
In total, approximately 1.7–2.7 million grids were generated to calculate the heat transfer of the steam generator housing for each model. Approximately 0.81–0.92 million interface calculation grids were generated for internal flow and information exchange for each model. A segregated solid energy model was used to calculate the heat transfer of the housing. For the housing heating wire, the heat source was set to consume 1370 W, which is the required power of the model, and the time step for the transient analysis was set to 0.25 s/step. The internal flow analysis condition was the unsteady state of multiphase flow. The Eulerian multiphase model was used to conduct the multiphase flow analysis, and the wall boiling model was used to perform the phase change analysis. The turbulence model for the numerical analysis of the multiphase flow is an improved form of the

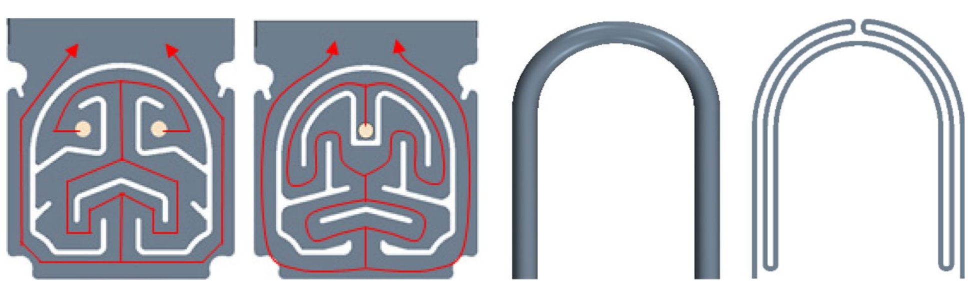


(a) 3D model (b) Flow channel 2D model

Fig. 2 Analysis model. (**a**) 3D model. (**b**) Flow channel 2D model

Table 1 Values of design parameters

	FL10-SH-UA (Base model)	FL10-FH-UA	FL10-FH-NA	FL15-FH-NA	FL15-FH-FA
Fluid channel length rate [%]	100	100	100	150	150
Water supply hole	2	2	2	1	1
Heater type [-]	Sheath heater	Film heater	Film heater	Film heater	Film heater
Heater arrangement [-]	U-Shape arrangement	U-Shape arrangement	Normal Film arrangement	Normal Film arrangement	Fluid channel following arrangement
3D model					

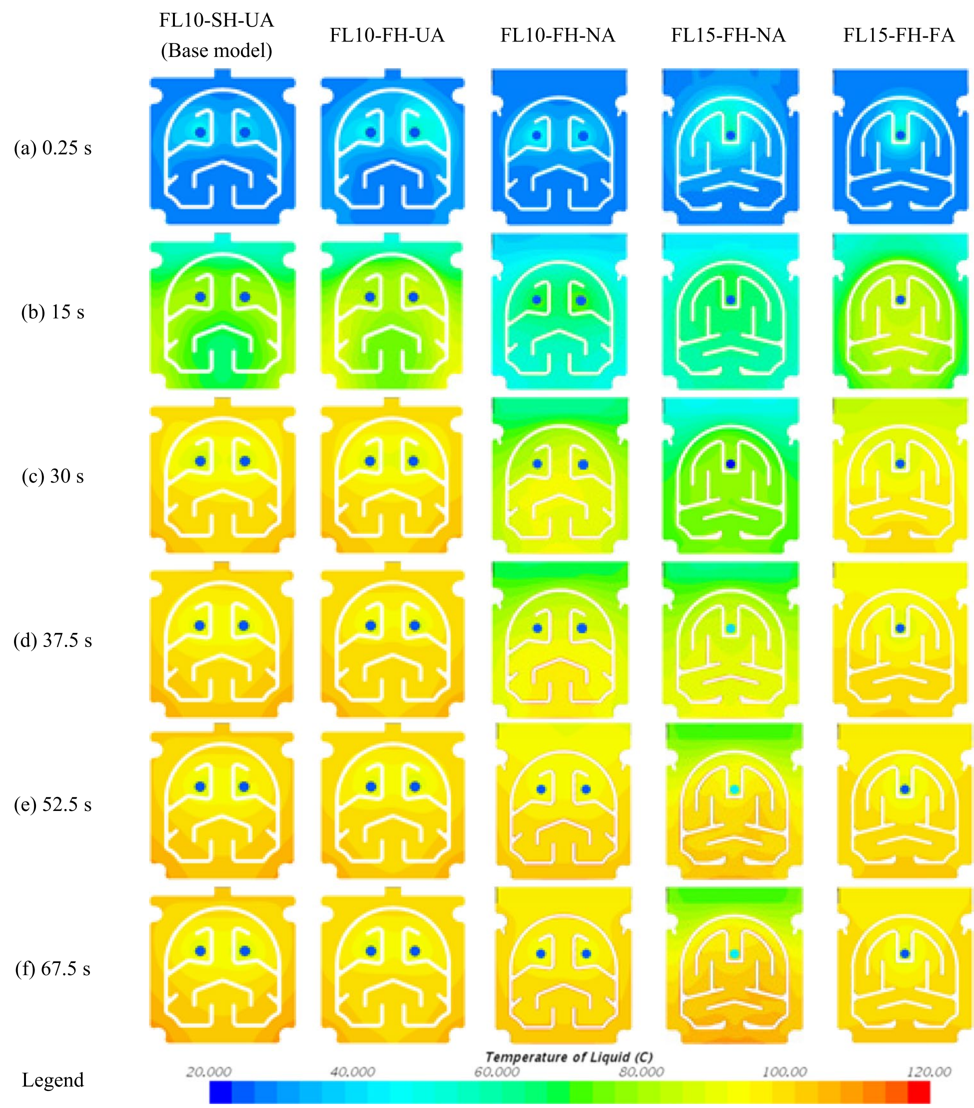


FL10 FL15 Sheath heater (SH) Film heater (FH)

(a) Fluid channel length rate (b) Heater type

Fig. 3 Design parameters. (**a**) Fluid channel length rate. (**b**) Heater type

Fig. 4 Temperature gradient of liquid



standard K-epsilon model, and a model that superimposes the turbulence of fluid and the additional turbulence caused by bubbles was used [13, 14]. Five prism layers were used to calculate the internal wall law. The inlet flow rate was set to 26 g/min and the outlet pressure was set to atmospheric pressure.

Analysis Results and Discussion

Heat Transfer Characteristics of Steam Generator Housing

The results of the heat transfer analysis of the steam generator housing showed that the temperature around the heating wire increased, and the heat was transferred in the vertical direction of the housing. In addition, first, the temperature around the returning heating wire was found to increase. Furthermore, the heat was not appropriately transferred to the central flow path. We believe this occurred because the arrangement of the heating wire was not optimized. The performance of the sheath heater was also compared to that of the film heater. In the case of FL10-FH-UA, which has the same type of heat wire arrangement, the heat transfer proceeded rapidly from the bottom, and consequently, the temperature did not rise excessively. In the case of the base model FL10-SH-UA, while the temperature increased to approximately 150 °C in the area where the heating wires were in direct contact, the maximum temperature was approximately 140 °C when the film heater was used in the model. To check the effect of the shape of the film heater on the performance, a U-shaped heating wire, a general film heater, and a flow path-following film heater were modeled. Consequently, in the case of the general film heater-type, the

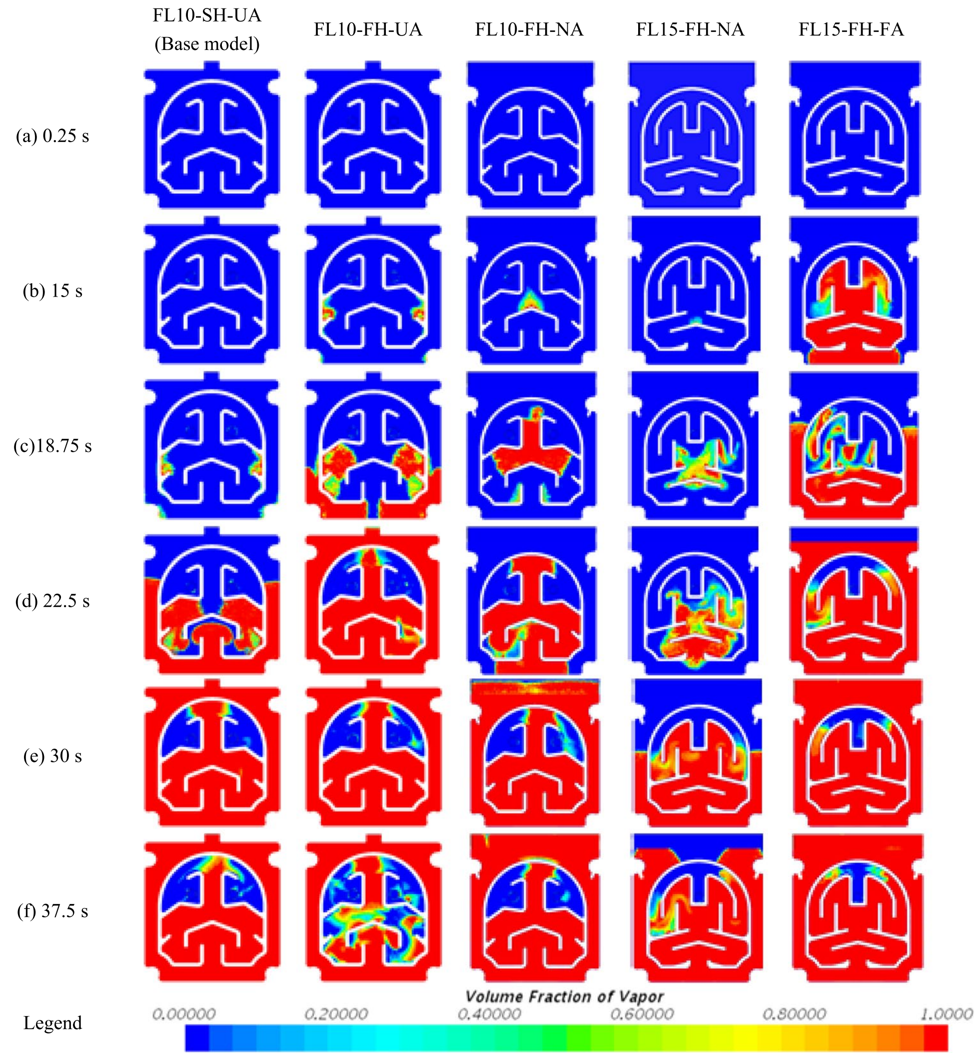


Fig. 5 Volume fraction of vapor

temperature increased from the center, and as the flow path became more complex, the heat was less evenly distributed.

Internal Flow Characteristics of Steam Generator

The internal flow analysis of the steam generator was conducted to analyze the volume fraction of the steam. The volume fraction that can be used to estimate the temperature distribution and boiling effect of water in a liquid state is the ratio of the volume of water vapor per unit volume and can be used to analyze the effect when liquid water is boiled above 100 °C. The temperature distribution at each time is shown in Fig. 4, and the volume fraction distribution of steam with time is shown in Fig. 5. In the case of the volume fraction, because boiling occurs within the first 0–25 s, the time was finely divided from the first occurrence. In FL10-SH-UA (base model), boiling started after 18.75 s, and steam was discharged to the outlet after 22.5 s. It was confirmed that the boiling point started at the area where the heating wire was installed, and from the side rather than the center. We believe this was due to the U shape of the heating wire. In addition, the temperature of the U-shaped heating wire increased from the outside, and the temperature of the general heating wire and the flow path that follows the heating wire increased from the center of the flow path. In the case of the volume fraction, similar to the increase in the liquid temperature, steam was formed outside the U-shaped heating wire, and the vapor was formed at the center of the general heating wire and the flow path that follows the heating wire.

Analytical Consideration

Comparison of Steam Generation Time and Ejection Time

The steam generation time and steam ejection time of the models considered in this study are shown in Fig. 6. The steam generation times of all models were lower compared to that of the base model. FL15-FH-FA generated steam

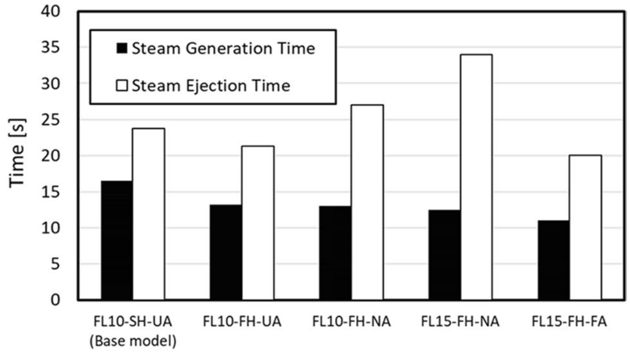


Fig. 6 Steam generation and ejection times

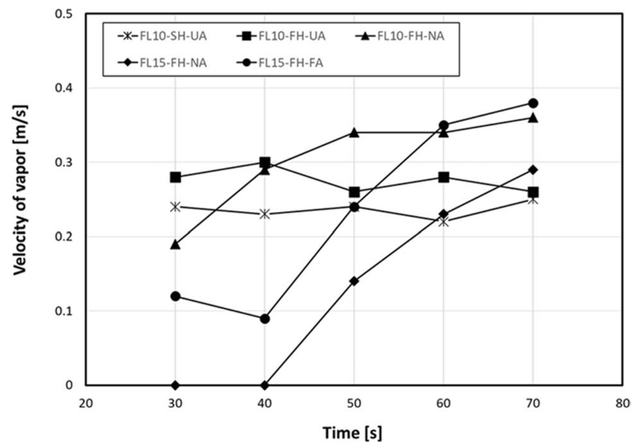


Fig. 7 Velocity of vapor at outlet

approximately 5.5 s faster than the base model, which was an improvement of 33.3%. FL10-FH-UA generated steam 2.25 s faster than the base model, which was an improvement of 19.7%. In terms of the steam ejection time, FL15-FH-FA showed an improvement of approximately 17% compared to the base model. The models with a delayed ejection time were FL10-FH-NA and FL15-FH-NA, and the performance of these two models were degraded by approximately 14% and 58%, respectively [15].

Comparison of Steam Ejection Rate and Volume Fraction

The average velocity and volume fraction of vapor at the outlet of the models after 30 s are shown in Figs. 7 and 8, respectively. The base model and FL10-FH-UA ejects steam while maintaining a relatively constant speed. The steam rate of FL10-FH-NA, FL15-FH-NA, and FL15-FH-FA increase rapidly after 40 s. We believe this difference was due to the arrangement of the heating wire. In most models, the volume fraction of steam is stable; however, FL15-FH-NA generates steam after 40 s. We believe this was due to the fact that the steam flow path was expanded by 50% compared to the base model. In FL15-FH-FA, the steam flow path was extended by 50% compared to the base model; however, because the heating wire was arranged along the flow path, the rapid vapor ejection that was observed in FL15-FH-NA, was not observed in FL15-FH-FA [15].

Conclusion

In this study, the performance of the sheath heater and the film heater were compared and analyzed, and a study on the heat transfer pattern according to the arrangement of the heating wire was conducted. To inspect the heat transfer performance, the external heat transfer and internal flow characteristics of the steam generator were analyzed, and a study on the performance of the steam generator according to each design variable was also conducted.

1) Among the models analyzed in this study, FL15-FH-FA showed the best performance. Compared to the base model(steam generation time 16.5 s, steam ejection time 23.75 s), the steam generation time of FL15-FH-FA was improved by 33.3%(5.5 s), and the steam ejection time was improved by 17%(3.75 s). This was because the heating wire arrangement of the film heater was optimized along the water path.
2) The U-shaped heating wire arrangement enabled a stable steam injection, and in the case of the general heating wire and the heating wire following the flow path, the internal steam was formed at the center due to the heating wire arrangement, and the temperature along the perimeter of the flow path increased and vaporized.
3) The base model and the FL10-FH-UA model ejected steam while maintaining a relatively constant speed. The steam ejection rate of FL10-FH-NA, FL15-FH-NA, and FL15-FH-FA increased rapidly after 40 s. We believe

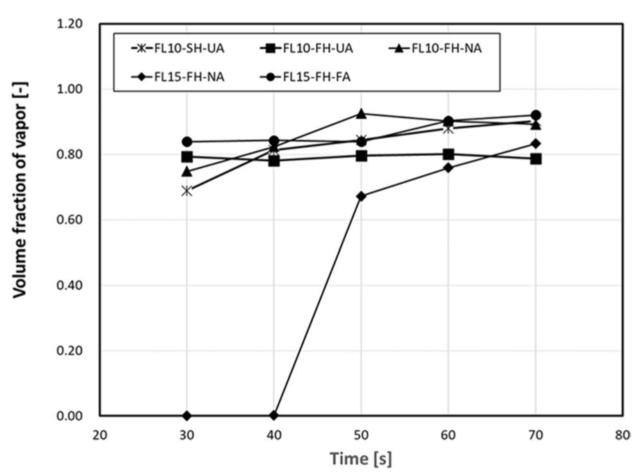


Fig. 8 Average volume fraction of vapor at outlet

that this difference was due to the arrangement of the heating wire, where the steam flow path was expanded by 50% compared to the base model.

4) In the FL15-FH-FA model, the steam flow path was extended by 50% compared to the base model; however, because the heating wire was arranged along the flow path, the rapid steam ejection that was observed in the FL15-FH-NA model, was not observed in the FL15-FH-FA model.

Here, we performed an analytical study of the heat transfer and internal flow of the handy steam iron. We believe that the analysis results can be applied to various fields due to the advantages of the film heater package, free pattern design, and economy of printed electronics.

Acknowledgments This paper has been summarized and revised from J-H Hwang's Thesis [15].

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