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ANALYSIS OF A NOVEL HIGH PERFORMANCE INDUCTION AIR HEATER

by

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This study represents an experimental and numerical investigation of the enhanced prototypes of the induction air heaters. For this purpose, flow field is enhanced in order to avoid turbulence. The air mass flow rate, outlet construction and the application of insulation of the outer surface of the heater were selected as the performance enhancing parameters. Depending on the exit construction, the new designed prototypes are named as K-2 and K-3. Experiments were performed under two groups for three various flow rates. In the first group, non-insulation situation is examined. In the second group tests, insulation is applied to the outside of windings and inlet-outlet flaps which constitute the boundary of the control volume for the prevention of heat losses.

The increasing flow rate boosted the thermal efficiency by 9%. Each of insulation and enlarging exit cross section increased the thermal efficiency by 13%. It was observed that the thermal power transferred to air with the new prototypes increased about 246 W more than the previous designs. The thermal efficiencies of the K-2 and K-3 type heaters were calculated as 77.14% and 87.1%, respectively.

Key words: *induction, air heater, induction fluid heater, thermal analysis, CFD,*
energy efficiency

Introduction

The studies about energy efficiency are significantly increasing with respect to the increasing demand [1, 2]. Therefore, the effective usage of energy became important in addition to the researching alternative energy resources [3, 4]. In a fact sheet of the European Commission, it says that heating and cooling application held 50% of annual energy consumption of Europe in 2016. The main resources for heating and cooling applications and their percentages are; natural gas (46%), coal (15%), biomass (11%), fuel oil (10%), nuclear energy (7%), renewable energy sources (mainly solar, wind and hydropower, about 5%) and other renewables and fossil fuels [5]. In the field of residential, industrial or public space heating applications, there are many options to supply heat and using various technologies. These main technologies can be classified as; heat pumps, resistance, gas-fired, solar, infrared and biomass fired space heaters, and the induction air heaters which are considered in this study [6-9]. All of these technologies have advantages for specific purposes. The electrical resistance heaters are one of the oldest solutions for residential space heating. It can convert electrical energy to the thermal energy efficiently. Solanki *et al*. [10]

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performed simulations to test the hybrid solar collector which mounted on a wooden channel. They found the electrical and thermal efficiencies of the hybrid collector 8.4% and 42%, respectively. Ali *et al.* [11] investigated double pass solar air heater system to find the best efficiency. For this purpose, they run their experiments under four different configurations. They used an absorber plate, added paraffin wax as a thermal storage medium, put aluminium and steel rods as a thermal enhancer. They have concluded that the third configuration showed the best performance with 96% efficiency. Turanjanin *et al.* [12] made the energy and economy analysis for different home heating systems using TRNSYS simulation cod. They have compared the heating systems which use natural gas for boiler and pellet as a heat source for direct heating (biomass boiler) or heat source for a heat pump. They have considered the life time of all heating systems as 15 years. Considering the life time for all systems, their results showed that, heating with gas boiler is the best economical system. However, in the perspective of energy usage, the heat pump showed the best performance. Furthermore, Kewou *et al.* [13] implied that the usage of air in industrial drying process employs up to 15% of all industrial energy with low thermal efficiency between 25-50% .The literature given here are good and illuminating studies on space heating. But none of them considers the induction air heating as an alternative.

The induction theory was first introduced by Michael Faraday in 1831. After the discovery of induction theory, the studies made by Lenz and Neumann in 1845 showed that the induced voltage heats the conductive material [14]. The usage of induction in many industrial processes such as preheating, surface hardening and tempering were increased due to its economic ease of usage in recent days [15]. Nowadays, the induction heating systems considered as the competitors to the natural gas fired furnaces in terms of energy consumption and size are also frequently encountered in the domestic applications. It is also possible to find induction in many different heating processes, such as sterilization of medical equipment, asphalt heating and *etc.* [16].

Induction heating systems are widely used in metal heating processes because of their many advantages such as being environmentally friendly system, short application time and low thermal losses [17]. It has been implied that a more economic and ergonomic system can be obtained by incorporating induction heaters in the extrusion process of aluminium materials [18]. Luo and Shih [19] found the heat flux that supplied from the induction heater by using the thermal changes in the single-carbon steel as a working material. Nian *et al.* [20] used the induction heater to heat the mould surface. Pleshivtseva *et al.* [21] investigated the usage of induction in preheating of metals before hot forming. Tavakoli *et al.* [22, 23] studied the effect of workpiece dimensions on induction heating. On the other hand, the differences between gas fired furnaces and induction heaters have investigated [24]. The literatures given in this paragraph provide useful insight into induction heating of metals. But they are not concerned with fluid heating.

Curran and Featherstone implied that induction can be used for fluid heating applications as it used in metal heating processes [25]. Induction liquid heaters have become to compete with resistive liquid heaters with the expansion of the field of application [26]. Kolesnikov and Andreev [27] investigated the heat transfer characteristics of a fluid flow inside the ring-shaped metal channel by applying a magnetic field. Altintas *et al.* [28] designed a microcontroller based induction liquid heater. On the other hand, induction heaters have domestic applications as well as industrial applications. Acero *et al.* [29, 30] improved and characterized the resistance and power consumption of induction by placing between two planes for the kitchen applications. Fenercioglu and Kartal [31] used Eddy currents which forms the basis of induction for decomposition of non-ferrous metals. Cetin [32] designed and analysed a kitchen type induction heating system in his master thesis. Induction heating systems are also used for polymerization, bitumen heating and sterilization [33-35].

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Using induction heating for the purpose of air heating was introduced by Burnett [36, 37] who prioritized the investigation of the transformer and coil sections of the developed induction gas heater systems. After this invention, Virgin [38] dealt with the electrical discipline of the system called the electromagnetic induction air heater and described the system as a steam-generating energy converter at the basis of his study. Similarly, Iguchi supported the idea that explained as in [38], however he did not include the thermal analysis in the study [39]. Despite the fact that the research and application area of induction heaters has such a wide variety, the electrical discipline of the systems has been taken into consideration in the studies for fluid heating. Additionally, the air heating process and the examination of thermal analysis have not been satisfactorily analysed in the literature [40].

In this paper, the thermodynamic analysis of the induction air heater system was performed. The system is developed to be an alternative to supply hot air requirement for fruit and vegetable drying processes such as in [41, 42]. In addition, the suggested improvement alternatives were made in the system that previously described as K-0 and K-1 type prototypes [43]. Following the suggestions, the constructions named K-2 and K-3 was developed and their dimensions were given in the next section. As a result, the decrease in thermal losses and hence the increase in thermal efficiency is ensured. In addition, the experimental results were examined and the CFD analysis was performed to determine the accuracy of the results.

Material and method

Thermal analysis

In this study, the modifications for the thermal development of the induction air heating system have been experimentally and numerically investigated. The experiments for each prototype were performed under two groups (insulated and uninsulated), considering three different flow rates. In the first group tests, uninsulated situation is examined. In the second group tests, insulation is applied to the outside of windings and inlet-outlet flaps which constitute the boundary of the control volume for the prevention of heat losses. The system was evaluated as steady flow system and thermal analysis was performed according to 1st Law of Thermodynamics. The inlet part of the induction air heating system is designed to be conical in dimensions of 140×68.5 mm with a length of 129 mm. K-2 type heater outlet is designed as conical in dimensions of 140×90 mm and K-3 type heater outlet is designed according to ASME B 16.9 standard, in dimensions of 140×114 mm as a concentric reducer as seen in fig. 1. Inside of the shell was considered as the control volume boundary. The induction heating system cannot transfer entire the electrical energy from the coils to the air due to the heat losses from the surface of the shell that are; radiation and natural convection. In this study, the procedure given
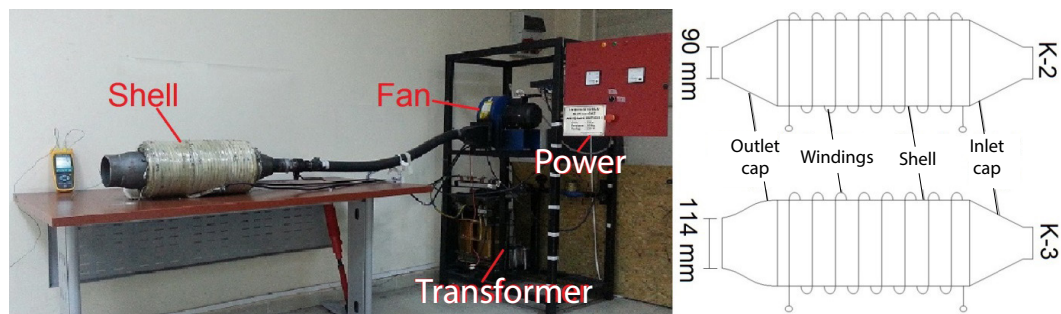

Figure 1. Experimental rig and the schematic view of K-2 and K-3 type induction air heater prototype

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by reference [44] for natural convection and radiation heat losses were applied. The magnitude of the radiation loss was calculated with the average of the surface temperature measured via a thermal imager. Since the control volume is accepted as the inner side of the shell, the boundary conditions can be accepted as constant heat flux from the sides and steady flow from the both ends. At the beginning of the experiments the system boundaries are at the room temperature and at the end of the experiments the side boundary of the system is at the inner temperature of the shell. During the entire process, heat flux and the mass flow rate assumed constant.

Other parameters that cause energy losses in the induction air heater are kinetic energy variation and friction-discharge losses. Although these losses are small, proportional to the size of the working system, they may cause too much energy loss when the system sizes are increased.

The fluctuations in the fluid density cause changes in the velocity of the fluid and its' kinetic energy. The kinetic energy difference can be calculated:

$$\Delta P_{KE} = \frac{1}{2}\dot{m}\left(V_o^2 - V_i^2\right) \tag{1}$$

where ΔP_{KE} [W] is the kinetic energy difference, V_o [ms^{-1}] – the outlet velocity of the air and V_i [ms^{-1}] – the inlet velocity of the air.

The amount of heat transferred to the fluid increases depending on the roughness coefficient of the surface in the system. However, resistance of the solid surface limits the fluid movement. This limitation is reflected in the system as friction losses. In addition to friction losses, there are partial losses at the connection points of the parts, such as inlet-outlet caps and in the areas where the cross-section changes. Such losses are called local losses. Within the scope of this study, the losses are also referred to as discharge losses. The discharge losses are obtained by the sum of friction and local losses and can be expressed in eq. (2) [33].

$$\Delta P_{DL} = \rho g\left(f\frac{L}{D} + C_D\right)\frac{V^2}{2g} \tag{2}$$

Here ΔP_{DL}, f, L, and C_D represents discharge losses [W], friction factor, pipe length [m] and discharge loss coefficient, respectively. The total loss from the system can be calculated:

$$P_{\Sigma L} = \dot{Q}_{nc} + \dot{Q}_{rad} + \Delta P_{DL} + P_{other} \tag{3}$$

Here P_L [W], refers to the total power loss of the system, and is the loss due to leakage. It is necessary to know the induction power fed to the system in order to calculate the thermal efficiency which is the main aim of the work. For this reason, electrical power that was obtained experimentally is converted to the thermal power that is induced in the coil by using induction efficiency as given in eq. (4).

$$P_b = P_{ind}\eta_{ind} \tag{4}$$

Here P_{ind} [W], refers to the induction power, is the amount of power that is rejected from the coil, and is the induction efficiency [45]. In the analysis, the thermal efficiency of the system was defined as the ratio of the power transferred to the air by the electric power reaching the inductor:

$$\eta_{th} = \frac{\dot{Q}_{air}}{P_b} \tag{5}$$

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Since the steady-flow conditions of the system were evaluated in the study, eq. (6) was employed to assess the steady-flow [15]:

$$\Delta T_\varepsilon = \frac{\sum_i^n (T_{i-1} - T_{i-2})}{n - i} < 0.3 \tag{6}$$

Table 1. Measurements and instrument specification

Item	Instrument	Range	Accuracy
Temperature measurements	Multi-channel thermometer with K-type thermocouple, Data logger	−100-1300 °C	± 0,7 °C, ± 0,1% reading
Velocity measurement	Testo 410-2 anemometer	0,4-20 m/s	±0.2 m/s, ± 2% measured value
Temperature distribution measurement	Testo 875 thermal camera	0-350 °C	±2 °C, ±2% of measured value
Power measurements	Brymen BM-157 clamp meter	0-600 kW	±4,5%, + 6 digits

The flow rate is adjusted by a valve placed in the inlet of the test apparatus. In order to prevent heat losses the control volume that is the outside of the shell, inlet and outlet caps are insulated. The results were compared with K-0 and K-1 type induction heaters and confirmed with CFD analysis.

The measurement range is set to 5 minutes after a steady-flow is achieved. The devices given in tab.1 were used for the measurements. The uncertainty was calculated as 5.7% for K-2 experiments and 8.1% for K-3 experiments.

Numerical modelling

The induction heater was modelled with 2-D-axisymmetric model due to symmetrical geometry as shown in fig. 1. The diameter and length of the shell are considered 140 mm and 450 mm, respectively. The inductor which has 374 windings and inner and outer diameters, 160 mm and 237 mm, are introduced to the model. The surrounding air of the heater system also included to the geometry. The resulting geometry of the K-2 type prototype can be seen in fig. 2.
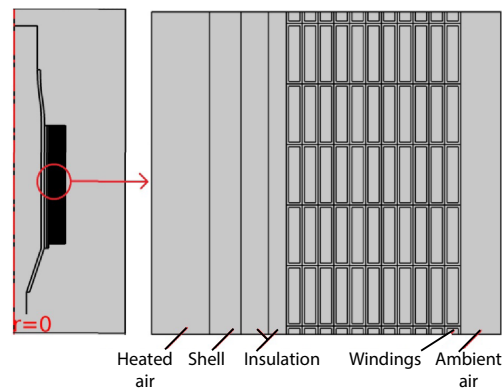

Heated air   Shell   Insulation   Windings   Ambient air

Figure 2. The K-2 type geometry for the simulation

The materials of inductor, shell and isolations were selected as copper, ST-52 steel, glassfiber and temperature resistance thermoplastic, respectively. The thermophysical properties of the materials were introduced as a temperature dependent as indicated in Cheng *et al*. [46] and Hadjab and Kadja [47].

The non-isothermal flow and induction heating are selected as a main physics. The sub-physics are as follows: the magnetic fields, heat transfer in solids, heat transfer in fluids and turbulence flow (*k-ε*). The power measured from the experiments was introduced to the inductor as a boundary condition. On the other hand, the mass flow rate that obtained from the experiments was introduced to the model to solve the Navier-Stokes equations. The inlet temperature of the air was taken as ambient temperature in the heat transfer equations. The physics

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controlled normal quality mesh that is automatically generated by the simulation program (triangular elements) was used to solve the model and the mesh size is selected as extremely fine.

Results and discussion

The K-2 and K-3 heaters were designed according to avoid disturbing the flow. The inlet and the exit sections are widened and the effect of the change of the inlet and exit construction on the performance was investigated experimentally. The experiments were performed for insulated and uninsulated cases with 3 various flow rates. The effect of insulation and the flow rate were also observed.

Investigation of flow rate effect

In the first experiments for each construction type, the valve was set up to 33-66% and 100% open positions. For accurate comparison of the analysed cases, the flow rate, the power input, the measurement points were controlled and kept constant. The air speed increased and the duration of the air transition through the system has been shortened. Thus, the cooling effect increases, resulting in a reduction in the internal surface temperature of the shell and this decreases the temperature of the coil. Hence the resistivity of copper wires decreases since more heat is rejected from the coil. As a result, the measured electrical power in the coil was higher as the flow rate increases, although the structure remained unchanged, tab. 2. The decrease of outlet temperature in the insulated case was because of the fluid velocity is measured higher. The flow rate was set by valve position, thus different flow rates were obtained in the experiments. Variation of the flow rate changed the cooling effect. Therefore, the energy transferred to air and dimensionless parameters were considered for the comparison. Finally, the efficiency of the insulated heater was calculated to be higher the uninsulated heater.

Table 2. Measurements of K-2 and K-3 type induction air heater prototypes

	Parameter		K-2			K-3		
Uninsulated	Valve position		33%	66%	100%	33%	66%	100%
	$\dot{m}\cdot10^3$	kg/s	9.87	17.71	28.00	8.20	16.10	28.50
	$T_{o,a}$	°C	88.65	62.05	49.85	95.40	66.20	51.20
	$V_{o,a}$	m/s	2.00	3.45	5.45	1.00	1.75	2.95
	P_b	W	581.66	667.63	785.09	612.41	694.5	800.47
	P_g	W	981.61	978.54	1039.46	930.07	974.85	1015.19
Insulated	Valve position		33%	66%	100%	33%	66%	100%
	$\dot{m}\cdot10^3$	kg/s	15.95	23.61	29.95	15.90	24.10	29.10
	$T_{o,a}$	°C	72.10	60.60	52.80	72.10	54.70	50.90
	$V_{o,a}$	m/s	2.90	4.20	5.35	1.67	2.75	3.30
	b	W	650.28	746.91	788.47	755.29	827.61	896.31
	P_g	W	988.91	1016.83	1022.07	960.1	1015.02	1029

For each flow rate, K-3 prototype transferred more heat to the flow than the K-2 prototype. In the K-2 prototype, outlet geometry is slightly sharper than the K-3 prototype resulted in larger vortices at the inlet and outlet and less heat was transferred as the fluid had more losses

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in the shell. As a result, the cooling effect of the fluid on the shell was less and the overall temperature of the system was more.

Effect of insulation on the thermal losses

The insulation reduces the thermal losses from the outer shell, fig. 3. It was observed that according to the uninsulated case, the insulation application saves 115.21 W and 121.28 W in K-2 and K-3, respectively.

The total heat losses from all proto- types developed so far were compared with each other. The least total heat loss is calcu-

Figure 3. Natural convection and radiation losses of K-2 and K-3 type prototypes with/ without insulation

lated to be from K-3 prototype. This results shows that enhancing the flow field has a positive effect on thermal losses.

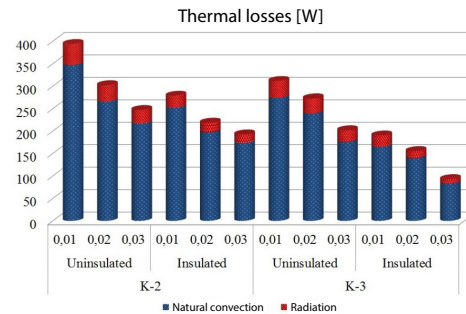### Investigation of construction

The CFD analysis of induction heater designs, flow rate and internal temperature distributions were performed by using a model that has validated in [43]. In the model, the velocity of the air decreased when the outlet construction of the shell was widened as seen in fig. 4. Although the K-2 type heater evacuated the air faster than the K-3 type heater at the same flow rate, the air outlet temperature was found to be close to both types of heater.

According to the CFD analysis, the velocity of the fluid in the K-3 construction was found to be slower through the shell than in the K-2 type as shown in fig. 5. That is, the vortexes formed in the K-2 type heater are denser than the vortices in the K-3, thus the inner wall temperature distribution is became higher.

The temperature distribution along the centre axis is also higher in the K-2 type heater than in the K-3. In the K-3 heater, the speed and therefore the kinetic energy is low, so that the thermal energy transferred from the system to the air is relatively more.

The air leaves the system after transferring the heat from the inner wall of the shell. The increase in flow rate in the system increases the cooling effect of the air and provides more heat transfer. However, as the energy transferred to the unit mass decreases, the average air outlet temperature and total heat transfer increase, resulting in lower wall temperatures. However, despite the increase in the average air outlet temperature and the total heat transfer, the
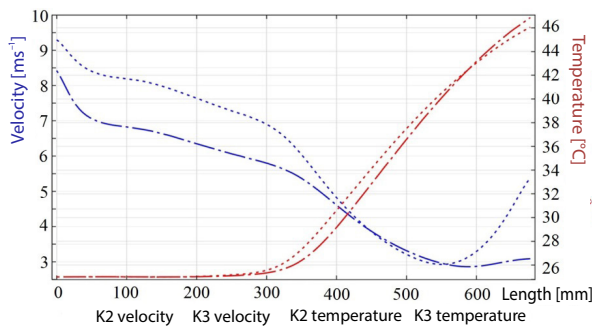

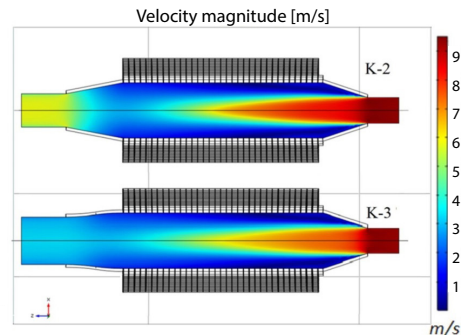**Figure 4. Temperature and velocity variations through the centreline**

Figure 5. Velocity contours of K-2 and K-3 type prototypes for non-insulation condition

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wall temperature of the shell became lower because the energy transferred to the unit mass was decreased.

It is seen that the velocity of the fluid is higher along the shell in the K-2 prototype than the K-3, except for the zones between 450-550 mm where the outlet section narrowing begins, by means of the influence of having smaller outlet diameter. Therefore, the Re number is higher throughout the shell in the K-2 type heater as observed in fig. 6. In other words, the effect of turbulence in the heater becomes greater.

The increase in turbulence also increases the duration of air passing time and thus the heat transfer time and that has a negative effect on the heat transfer in the K-2 prototype. As a result, the fluid flows somewhat hotter in the 0-300 mm range in the shell, and after 550 mm, the speed increases because of the narrowing outlet cross-section but the temperature decreases as seen in fig. 7. An increase in the amount of energy transferred to the air together with the increase in the flow rate can be seen in both heater types as shown in tab. 3.
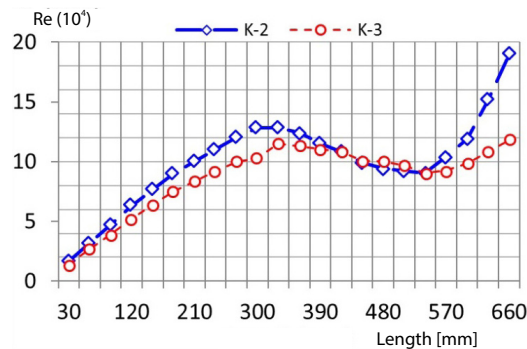

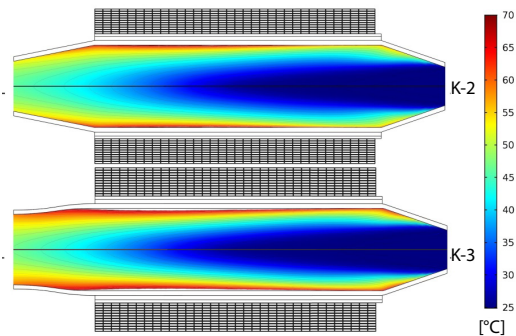**Figure 6. Average Reynolds numbers of prototypes for non-insulation condition**

Figure 7. Temperature contours of K-2 and K-3 type prototypes for non-insulation condition

Table 3. Thermal efficiency analysis results of the K-2 and K-3 type induction air heater prototypes

	Parameter		K-2			K-3		
	Valve position		33%	66%	100%	33%	66%	100%
	$\dot{m} \cdot 10^3$	[kgs^{-1}]	9.87	17.71	28.00	8.20	16.10	28.50
Uninsulated	$\dot{Q}_h$	[W]	581.66	667.63	785.09	612.41	694.5	800.47
	$P_{\Sigma L}$	[W]	393.97	302.61	248.7	311.66	273.37	204.22
	η_{th}	[%]	59.26	68.23	75.53	65.85%	71.24%	78.85%
	Valve position		33%	66%	100%	33%	66%	100%
	$\dot{m}$	[kgs^{-1}]	15.95	23.61	29.95	15.90	24.10	29.10
Insulated	$\dot{Q}_h$	[W]	650.28	746.91	788.47	755.29	827.61	896.31
	$P_{\Sigma L}$	[W]	278.9	219.44	194.14	190.66	157.31	96.32
	η_{th}	[%]	65.76	73.45	77.14	78.67	81.54	87.1

However, the total loss of the system was reduced as the flow rate and the heat transfer increased. The amount of energy transferred to the air was higher in the K-3 type than in the K-2 type heater, while the total amount of loss was less and the thermal efficiency was increased in

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parallel with the expansion of the outlet cross section at each flow rate. Likewise, the amount of energy transferred to the air was increased at each flow rate and thus the thermal efficiency was increased while the total amount of loss was reduced by insulation application in K-2 and K-3 type heaters.

The total losses in the K-0 and K-1 induction heaters for the uninsulated cases were given as 830.8 W and 457.1 W, respectively [15, 43]. These values were reduced to 393.97 W and 311.66 W in the prototype K-2 and K-3 in the uninsulated case. The thermal efficiency, which was calculated to be 29.09% for the K-0 type and 56.3% for the K-1 type heater, is increased to 77.14% for the K-2 prototype and 87.1% for the K-3 prototype due to regulation of the flow field and insulation improvements.

Conclusions

The object of this study is to investigate the effects insulation and flow field enhancement on the performance of the induction air heaters. The new heater prototypes (K-3 and K-4) were designed as a blank shell and the exit of the shell was extended so as not to disturb the air flow according to earlier prototypes. The sharp inlet and exit are preferably curved appropriately.

The experiments for insulated and uninsulated cases were repeated for 3 different flow rates according to the inlet valve position. It was observed that the flow rate, the enlarged exit cross section and the insulation increase the thermal efficiency between 3-9%, 3-13%, and 2-13%, respectively. The thermal power that is transferred to the air increased by an average of 246 W with the flow rate increment and insulation. The min. total loss and the max. thermal efficiency were calculated to be 96.32 W and 87.1% respectively in the K-3 heater through the prototypes developed so far.

For further studies, it is recommended to re-design and repeat the tests with different geometric structures and shell types with different materials. We forecast that the thermal efficiency may be increased if the exit and inlet diameters are made equal and the air flows both inside and outside of the coil to cool the windings. Finally, it is estimated that induction heating systems can also be used for hygienic air supply if the inner surface is appropriately coated.

Acknowledgment

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