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COMPARISON OF NATURAL GAS FIRED AND INDUCTION HEATING FURNACES

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ABSTRACT
Generally, in steel processing systems, steels are heated via induction or combustion furnaces. Natural gas fired furnaces have installation costs advantage and induction furnaces have the advantages of less scale formation on the surface of the workpiece as well as environmental reasons. The operation cost of both systems is a vital argument to be solved. In this paper, a natural gas fired and induction-heating furnace of a forging process was studied. Thermodynamic analysis was performed for the furnaces which heats the work piece up to 1300 C. The energy performances of both systems were analyzed and compared. The heating process is optimized and a hybrid process is suggested.

INTRODUCTION
To bequeath habitable environment, today's world has to pay attention to energy sources and usages. This well-known truth forced to change the energy policies of entire world. Today many countries encourage the tendency to the renewable resources. However, fossil fuels cannot be given up suddenly due to both the number of clean power plants and their low efficiencies. So, the critical energy demand cannot be individually supplied by renewable resources. Since the installed powers of renewables are not sufficient yet, the energy saving applications or saved energy is also assumed to be renewable by most academic communities.

INDUCTION HEATING
Induction heaters are used to provide alternating electric current to an electric coil (the induction coil). The induction coil becomes the electrical (heat) source that induces an electrical current into the metal part to be heated (called the workpiece). No contact is required between the workpiece and the induction coil as the heat source, and the heat is restricted to localized areas or surface zones immediately adjacent to the coil (1). It provides faster and more precise heating of local areas, consumes less energy and is considered environmentally friendlier than other methods. Other advantages also include lower labor cost for device operators, easy maintainability of the equipment, quality assurance, automation capability and high reliability. Induction heating is a complex process including electromagnetic, thermal and metallurgic phenomena. In this process an alternating electric current induces electromagnetic field, which in turn induces eddy currents in the workpiece. The induced eddy currents release energy in the form of heat, which is then distributed throughout the workpiece (2).

Laborelec (3) indicated that the principle of induction heating is mainly based on two well-known physical phenomena, electromagnetic induction and the Joule effect. The energy transfer to the object to be heated occurs by means of electromagnetic induction. It is known that an alternating current is induced in a loop of conductive material when this loop is placed in an alternating magnetic field. The formula is as follows:

$$U = d\varphi/dt \tag{1}$$

Were U is voltage (V), φ is magnetic flux (Wb) and t is time (s). When the loop is short-circuited, the induced voltage U will cause a current to flow that opposes its cause-the alternating magnetic field. This is the Faraday-Lenz law. If a massive conductor (e.g. a cylinder) is placed in the alternating magnetic field instead of a short-circuited loop, eddy currents (Foucault currents) will be induced (see Figure 1).

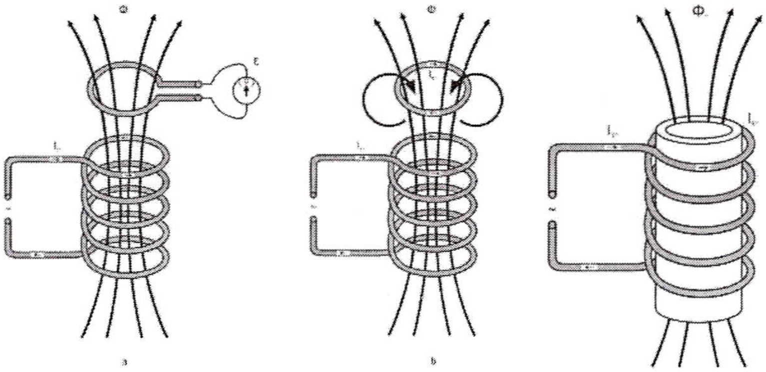

Figure 1: Faraday's Induction law.

The eddy currents heat up the conductor according to the Joule effect. When a current I [A] flows through a conductor with resistance R [O], the power is dissipated in the conductor. In most applications of induction heating, the determination of resistance R is not a simple matter due to the non-uniform distribution of current in the conductor.

Haimbaugh stated that power requirements are related to the amount of energy required to heat a workpiece and to the induction heating system power losses. The energy or heat content required to heat the workpiece can be calculated when the material, its specific heat, and the effective weight of material to be heated per hour are known. Higher power densities provide the ability to heat surfaces more rapidly. However, there may be limitations to the amount of power that an individual induction coil can handle (1). Power induced in the workpiece can be determined as:

$$P = U \,.\, I = R \,.\, I^2 \tag{2}$$

Where P is the power (kW). In literature there are several studies focused on heating of metal. In this study, since our scope is the heating of steels for hot forging, we allowed for data of the papers that are related to our subject.

Table 1. Power consumptions of various metals for hot forging heating. (4)

	Steel	Aluminum	Copper	Brass (CuZn 70/30)
Forging Temperature (°C)	1250	500	900	750
Power Induced (kWh/ton)	240	136	105	90
Power Consumed (kWh/ton)	350 – 400	280 – 300	230 – 250	180 – 190
Frequency (Hz)	50 – 10.000	50 – 4.000	50 – 4.000	50 – 4.000

Table 2. Average Power Requirements For Induction Heat Processing Of Common Metals (5) (kWh/tons).

Process	Carbon Steel	Magnetic Stainless Steel	Nonmagnetic Stainless Steel	Brass
Hot Forging	440,9	413,4	474,0	440,9
Hardening/Aging	275,6	286,6	-	358,3
Annealing/Normalizing	248,0	231,5	413,4	413,4
Warm Forming	192,9	-	275,6	-
Stress Relieving	165,3	55,1	220,5	220,5
Tempering	77,2	77,2	110,2	-
Curing of Coatings	55,1	55,1	82,7	121,3

The efficiency should also consider .The electrical efficiency is defined as follows (3, 9):

$$\eta_e = \frac{\dot{Q}_w}{\dot{Q}_e} \tag{3}$$

Where η_e is the electrical efficiency, $\dot{Q}_w$ is the required energy for heating material (kW) and $\dot{Q}_e$ is the electric energy consumed (kW).
In the Table 3 Laborelec (3) has given the efficiencies of induction systems as to frequency converters

Table 3. Induction installations general aspects with various frequency converters (3)

	thyristors	transistors	tubes
Efficiency	90-97%	75-90%	55-70%
Frequency range:	100 Hz - 10 kHz	up to 500 kHz	up to 3000 kHz
Power range:	up to 10 MW	up to 500 kW	up to 1200 kW

The data was provided from the workpiece that has widest diameter passing through the conductor. Efficiency reduces with diameter reduction, by means of the increment of air gap between the workpiece and inductor. The operating costs are compared in Table 4 by Poncin (4). He was indicated that, heating a steel workpiece to 1250 °C consumes 350 kWh/ton. In the table it can be seen that, overall operating cost of a gas fired heating furnace is the cheapest method.

In addition, installation costs of induction and gas fired furnaces were given by Mortland (5) in Table 5. In the calculations, Annual Energy costs, scale losses, scrap losses, labor requirements were taken in to consideration. As to the results ofMortland (5), the Total Annual Operating Cost of Induction Furnaces are more economical than the Gas Fired Furnaces.

As it can be seen from Table 4 and Table 5 the results are not coherent. Thus, it must be noted that, these calculated costs vary as to the place, plant and the operation.

Table 4. Actual heating costs of various processes given by Poncin (4)(Euro/ton).

	Induction	Gas	LPG
Labor	3,85	7,7	7,7
Fuel	28,02	13,27	56,04
M&O	2,98	5,95	5,95
Scale Losses	2,23	11,15	11,15
Amortisation Costs	15,37	7,68	7,68
TOTAL	52,45	45,75	88,52

Table 5. Installation costs of induction and gas fired furnaces given by Mortland (5).

Item	Induction Furnace	Gas-Fired Furnace
Installed Cost	\$600,000	\$200,000
Heating Efficiency	60%	15%
Annual Energy Cost	\$720,000	\$540,000
Scale Loss	1/2%	2%
Scrap Loss	1/4%	1%
Annual Scrap and Scale Loss Cost	\$150,000	\$600,000
Labor Requirement	1 Operator 1/4 Maintenance	2 Operators 1/2 Maintenance
Annual Labor Cost	\$60,000	\$120,000
Total Annual Operating Cost	\$930,000	\$1,230,000

The advantages of induction furnaces are aligned as follows (3-6)

Technical process

- Maintenance costs and spare parts costs are fair.
- High power density provides a compact installation and realize a quick heating.
- Floor space requirements are less.
- Induction offers the possibility of reaching very high temperatures
- Induction heating can be applied to specific area of workpiece
- Induction installations are suited for automation
- Recovers time and heat losses during feeding and receiving of work piece.
- No need to stock fuel.
- A significant portion of the heat losses can be recuperated
- Extreme purity is possible by working in a vacuum or in inert atmospheres
- The precise location of heating can be determined accurately
- The heating can be regulated precisely
- Environment and working conditions
- No production of flue gasses
- Induction installations generally have good efficiency although this efficiency also depends upon the characteristics of the material to be heated

Stefan and Günter recommended a hybrid furnace system that includes both with natural gas fired and induction furnaces. They advised that the material would heated up to 700-800 °C via the gas fired furnace and to 1200-1300 °C via induction furnace to avoid scale formation (7).

NATURAL GAS FIRED FURNACES

Natural gas fired furnaces (NGF) are somewhat simpler than the induction furnaces. You can see and hear the process in the furnace. The elements are familiar and known. These furnaces can be assumed as bigger scaled furnaces of our domestic ones. Therefore, most of the systems which are used in NGF are conventional e.g. loading system, walls, gas systems.

In NGF, main energy input is the combustion of natural gas. The electric, which is used to run the burners and air fans, may be considered as auxiliary energy. The total energy input via natural gas combustion can be calculated as;

$$\dot{Q}_f = \dot{m}_f \, . \, LHV \text{ (kW)} \tag{4}$$

Where $\dot{m}_f$ is the mass flow rate of natural gas (kg/s) and *LHV* is the Lovest Heating Value. Energy of flue gases may be calculated as;

$$\dot{Q}_{ex} = \dot{m}_{ex} \, . \, C_{ex} \, . (T_{ex} - T_o) \text{ (kW)} \tag{5}$$

The workpiece that is loaded to furnace may be at environment temperature or any pre-heat temperature. Even case the temperature difference can be calculated as the difference between inlet and exit temperatures. Thus, the total energy transferred to the work piece in the furnace can be calculated from;

$$\dot{Q}_{w} = \dot{m}_{w} \, . C_{w} \, . (T_{w} - T_o) \text{ (kW)} \tag{6}$$

Where $\dot{m}_w$ is the mass of workpiece loaded in 1 hour (kg/h), C_w is the specific heat of work piece in (kJ/kg°C) and T_w is the final temperature of the work piece (K). The radiation heat transferred from the hot surfaces simply can be calculated from;

$$\dot{Q}_{r} = \sigma \, . \, \varepsilon \, . \, A \, . (T_s^4 - T_o^4) \text{ (kW)} \tag{7}$$

The heat transfer via turbulent flow natural convection from the hot surfaces can be calculated from;

$$\dot{Q}_{nc} = \left[1{,}32 \, . \, \sqrt[3]{T_s - T_o}\right] . \, A \, . (T_s - T_o) \text{ (kW)} \tag{8}$$

The efficiency of a NGF can be obtained via direct and indirect methods. In the Indirect method, percentage of all losses through the total energy input must be calculated. In the direct method, proportion of the heat transferred to the workpiece to the total energy input via natural gas combustion can be calculated via the following equation.

$$\eta_{\Sigma} = \frac{\dot{Q}_w}{\dot{Q}_f} \tag{9}$$

Results and Discussion

The NGF considered in this study was installed 35 years ago, which has an old technology (Figure 1). The furnace has no exhaust system and naturally, has no recuperator or regenerator. The flame was blow out from the openings of the hatches. Thus, the thermal losses from the NFG were not based on only the radiation from the hot surfaces and exhaust gases. The opening losses were highly effective because of more than 1300 °C flame leakage. That means, the energy of flame with its radiation potential is inconsumable.

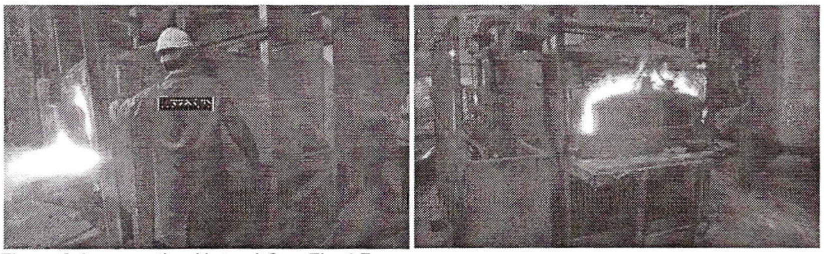

Figure 2 An operating Natural Gas Fired Furnace

In NGF systems, burners provide a stable combustion. By this means, it is easy to evaluate the volumetric or mass flow rate of natural gas. When natural gas flow rate read, total energy consumption can be easily calculated via the Eq. 4. In this study, Lowest Heating Value (LHV) of natural gas was taken from IZGAZ (Official Gas Distribution Company).

Table 7. Design Data and Energy Analysis of NGF

Fuel Consumption per Unit Time (sm3/h)	49,5
Lowest Heating Value of Natural Gas (kWh/Sm3)	10,64
Energy Consumption per Unit Time (kWh/h)	527
Combustion Time to Attain Steady State (h)	3
Natural Gas Consumption Until Steady State (sm3/h)	149
Total Energy Consumption Until Steady State (kW)	1580
Energy Requirement of 1 Tons of Steel (Design Capacity) (kW/h)	181
Energy Requirement of Steel Forged in Unit Time (Actual Data) (kW/h)	30
Q_{ex} Exhaust Losses (kW)	162
Q_{hs} Radiation Losses (kW)	25
Q_n Natural Convection Losses (kW)	19
Q_o Opening Losses (kW)	140
Q_T Total Heat Losses (kW)	205
Efficiency (Design Data) %	34,44
Efficiency (Actual Data) %	5,74

The results of the calculations and design data of the system, which was handled with in this study, were given in Table 7. The exhaust losses were obtained via Eq. 5. It was considered that all the 1300 °C hot stack gases were lost with their energy potential, since the NGF system has no exhaust, recuperator or regenerator. In the system, even some of the flame was thrown out from the openings of the furnace. In most of the applications, the opening losses obtained 5% of the total energy input. However, in this study it was calculated about 26% of total energy input. The main reason of this is, not only the loss of high temperature energy potential of the exhaust gases but also the energy potential of very high temperature flame and flames radiation potential. In this type of heating systems, the flame is wanted to be kept inside the heating zone because of its very high temperature, which is useful for convection and radiation. It is desired to finish the burning of natural gas inside the heating zone, but never outside. Because of this, the opening losses had a high percentage through the total energy input.

Hot surface radiation losses were calculated with Eq. 7. The mean temperatures of surfaces of the NGF were achieved via thermal camera (See Figure 3). In the system, the insulations were also not optimum. At some points on the furnace, the wall temperature was reached to 200 °C. This wall temperature is definitely not allowable temperature, because it means we are using the wall as a resistant heater to heat environment. Comparing to opening losses, hot surface losses are not seem to be serious. Nevertheless, the wall temperature should still reduced to T_o+40 °C.

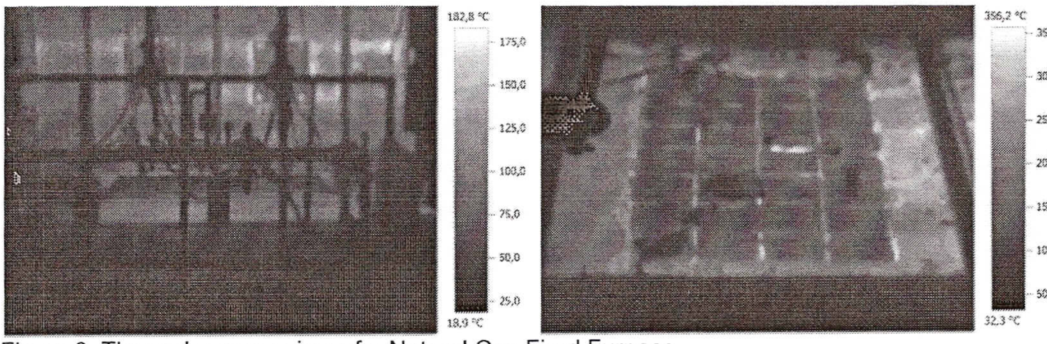

Figure 3. Thermal camera view of a Natural Gas Fired Furnace

Natural convection losses were calculated with Eq. 8, which is given by Tütünoğlu (8). At first glance, the natural convection may not seem to be high in proportion to other losses. However, if the dimensions of the furnace are considered, we can conclude that it has to be reduced also. The high wall temperature causes high natural convection losses as well as radiation losses.

Finally, the efficiency of both induction and NGF systems were calculated via Eq. (9). The data were collected from meters for natural gas and electric. It must be noted that, the NGF system starts up 3 hours before shifts. Because of this, additional operating hours of combustion system were considered. However, the effect of combustion to attain steady state is various. It depends on many parameters such as, the difficulty level of the work piece, operating time, production quantity, diameter of the work piece etc.

Table 8 Validation of Analysis and Comparison

	Induction Ref (4)	Induction Ref (5)	Induction Analyzed	NGF Analyzed
Total Consumption (kWh/ton)	375	441	755	527
Energy Requirement (Kwh)	188	188	299	30
Losses (kW)	187	253	361	722
Efficiency %	50,23	42,72	52,19	5,74
Heating Cost ($/ton)	52,08	61,24	69,91	158,94

In table 8 validation of the analysis results and comparison of the subject furnaces of this study were given. In the analysis the result obtained from the induction furnace is in a good agreement with (4 and 5). Mainly efficiency agrees with the literature. A slight difference may cause from Cos φ of the systems, but NGF system has a dramatic difference between induction furnace as well as the other natural gas fired furnaces given in literature. The most important and basic reason is; the analyzed heating system has no exhaust. If there were, we could have a chance to measure the combustion and recover the waste energy. The efficiency, which is given in Table 8, is the mean value of calculation results. A detailed analysis of efficiency of NFG is given in Figure 4. As it is mentioned, the efficiency of NGF depends on many parameters. If the order can be produced in 3 hours then the efficiency differs between 2,4-9,5% as to the production mass in one shift. If the mass of the production in one shift increases, efficiency of the system also increases. Let's consider that 500 kg will be forged, when it is forged in 3 hours the efficiency of the system calculated 2,4%. However, when production time extends to 8 hours, the efficiency of the system decreases to 1,5 %.

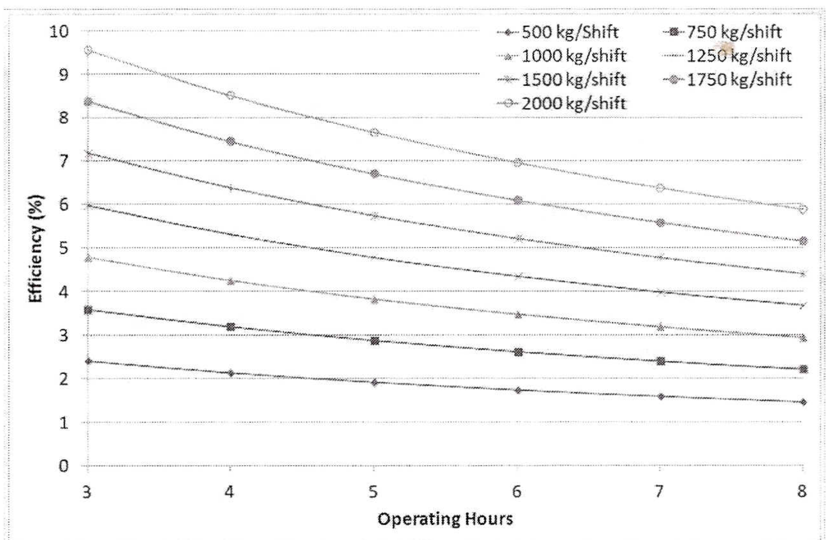

Figure 4 Efficiency of natural gas fired furnace considering load-per-shift and operating hours.

The efficiencies given in figure 4 are all very low. The system is old and ineffective. Because of this, a project proposal was given to East Marmara Development Agency (MARKA) to develop the NGF system and it is accepted. In the scope of the project, the system replacement of the old system with a modern NGF system was proposed. Taking into account that the most efficiency detractive topics are exhaust losses and opening losses, the projected system will have regenerators and economizers, tight lids. Since the most energy destructing section of the existing NGF are lids, to avoid the opening losses and leakage of the flame, a useful lid system is designed. In the designed NGF, loading system will minimize the load/unload losses as well as leakage. The wall insulation is considered to stabilize the wall temperature at (To+40) $^{\circ}$C, so the radiation and natural convection losses will also decrease. With the projected NGF, efficiency is supposed to increase up to 40%.

It is also decided that the next project will be about hybrid system that heat the workpiece up to 900 $^{\circ}$C by NGF and to 1300 $^{\circ}$C by induction furnace.

Conclusion

In this study, a thermodynamic analysis has performed for two types of furnaces of a forging facility as well as recent studies. The data are collected from an induction furnace and a natural gas fired furnace. It is seen that the efficiency of induction furnace is about 52%, which agrees with the literature. However, the NGF is very ineffective since the losses of the system are very high. Depending on the lot size and operating hours, the NGF efficiency was calculated max. 9.5% and minimum 1.4%. It is identified that the highest energy losses are exhaust (162 kW) and opening losses (140 kW) in order. In the current situation, heating the material with induction furnace is clearly profitable. Finally, the inefficient NGF should be remade with current technology.

Nomenclature

U	: Voltage (V)
φ	: Magnetic flux (Wb)
t	: Time (s)
P	: Power (kW)
I	: Current (a)
R	: Resistance (O)
η_e	: Electrical efficiency
$\dot{Q}_w$	: Required energy for heating workpiece (kW)
$\dot{Q}_e$	: Electric energy consumed (kW)
NGF	: Natural Gas Fired Furnace
$\dot{Q}_f$	: Total energy input via combustion of natural gas (kW)
$\dot{m}_f$	: Mass flow rate (kg/s)
LHV	: Lowest Heating Value (kW/kg)
$\dot{Q}_{ex}$	: Exhaust losses (kW)
$\dot{m}_{ex}$	: Exhaust flow rate (kg/s)
C_{ex}	: Specific heat of exhaust gasses (Kj/kgK)
T_{ex}	: Exhaust temperature (C)
T_o	: Atmospheric temperature (C)
$\dot{Q}_w$	: Total energy transfer to the work piece (kW)
$\dot{m}_w$	: Mass heated per unit time (kg/s)
C_w	: Specific heat of work piece (Kj/kgK)
T_w	: Temperature of the work piece (C)
$\dot{Q}_r$	: Radiation heat transferred from the hot surfaces (kW)
σ	: Stefan Boltzmann Constant (Kw/m^{2}K)
ε	: Emmisivity
A	: Area (m^2)
T_s	: Surface temperature (C)
$\dot{Q}_{nc}$	: Heat transfer due to Natural Convection (kW)
η_Σ	: Overall efficiency

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