Utilization of Domestic Gas Heater Exhaust Energy for Heating Water

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***Abstract** - The worldwide energy demands and its increasing cost in addition to the environmental problems of using the fossil fuels, has made the efficient use of energy inclouding heat recovery strategy in thermal systems. Although many equipments have been developed to re-use some of waste heat in large scales but there is few works on small scale and low grade sourses such as domestic gas heaters. This paper describes a water heating apparatus based on utilization of exhaust energy of domestic gas heater. The device is mounted on the roof, connected to the stack and the hot exhaust flows through its inner gear-shaped tube. The potential of heat recovery of this parallel-flow heat exchanger has been tested for 5.2 and 7.2kW heater powers and different exhaust temperatures in the range of 100-185 °C. The results indicate; at the desired water temperature 45 °C, the effective heating power enhances in the range of 290-940W proportional to the exhaust temperature and or gas heater power. The appliance could utilize up to 13% of total heat which is wasted, and it is fit to low grade, domestic gas heaters which are widely used and can supply hot water from low temperature exhaust gas even at 100 °C. Economical considerationns reveals that the payback time of installation this appliance is 4 years.*

Keywords **- Water heater, Heat recovery, Exhaust gas, Domestic heater, Buildings.**

1. INTRODUCTION

The worldwide increase in energy demands and the uncertainty of the future energy cost, made the energy conservation a major element in industry, transport and buildings [1] - [3]. Moreover the use of fossil fuels leads to environmental pollution and this is becoming a global problem. So, for example in the effort to reduce the production of carbon dioxide, the tumultuous Kyoto protocol has been made. Logically the economical and efficient use of energy is the first approach, as in industrial processes the waste heat recovery has been a solution [1], [4]- [6] so that the utilization of exhaust waste heat is now well known and is the basis of many combined cooling and power installations. Also, switching to use the more safe kinds of energy such as nuclear, winds and geothermal sources is essential. Among the fossil fuels, natural gas has been of great interest due to its world wide resources, simple transport and use, in addition to less environmental problems [7]. As a consequence, the gas pipeline networks have been developed and the traditional heaters have been replaced by gas types. Due to some technical limitations and safety considerations, the thermal efficiency of conventional domestic gas heaters is about 70% depends on heat power, structure of furnace chamber, and geometry of the stack. Although many types of equipments have been developed to re-use some of waste heat in large scales but there is few reports focused on small scales and low grade sources [8] - [11]such as domestic gas heaters which are widely used in the world's developing countries such as Iran. This paper explains the performance of a water heating apparatus which absorbs energy from domestic gas heater exhaust and can provide hot water for buildings applications.

2. WASTE HEAT ASSESSMENT OF GAS HEATER

Here, the waste heat rate from stack exit of a typical domestic gas heater fueled by natural or liquid gas is assessed. As a fair approximation the natural gas can be taken equivalent to methane, combusts with oxygen in the furnace chamber and its chemical reaction can be written as:

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O + 800\text{-}890\ \text{kJ} \qquad (1)$$

When the reaction occurs in the air, the more oxygen required, we denote the excessive oxygen consumption ratio as "r_1" parameter. Regarding that dry air just consists of 21% oxygen, and taking the rest as nitrogen. So, the real burning reaction of methane, can be written as:

$$CH_4 + 2\,r_1\,O_2 + 7.52\,r_1 N_2 \longrightarrow CO_2 + 2H_2O + 2(r_1 - 1)\,O_2 + 7.52\,r_1 N_2 \qquad (2)$$

In the case of liquid gas which consists of propane and butane, similar reactions occurs with less water in the exhaust gas and we denote their related excessive oxygen consumption ratios as "r_3" and "r_4" respectively and their burning reactions are as following. For propane it can be written as:

$$C_3H_8 + 5r_3O_2 + 18.8r_3N_2 \longrightarrow 3\,CO_2 + 4\,H_2O + 5\,(r_3 - 1)\,O_2 + 18.8\,r_3\,N_2 \qquad (3)$$

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and for butane:

$$2C_4H_{10}+13r_4O_2+48.88r_4N_2 \rightarrow 8CO_2+10H_2O+13(r_4-1)O_2+48.88r_4N_2 \quad (4)$$

According these, the excessive oxygen (and so the air) consumption coefficients can be calculated in terms of corresponding CO_2 percentage in the exhaust gas X_{CO2}, for example in the case of methane it can be determined as the following:

$$r_1 = \frac{1}{9.52}\left(\frac{1}{X_{CO2}}-1\right) \quad (5)$$

and so for propane:

$$r_3 = \frac{1}{23.8}\left(\frac{3}{X_{CO2}}-2\right) \quad (6)$$

and in the case of butane:

$$r_4 = \frac{1}{61.88}\left(\frac{8}{X_{CO2}}-5\right) \quad (7)$$

The variations of r_1, r_3 and r_4 coefficients versus X_{CO2} has been calculated and shown in Fig. 1.

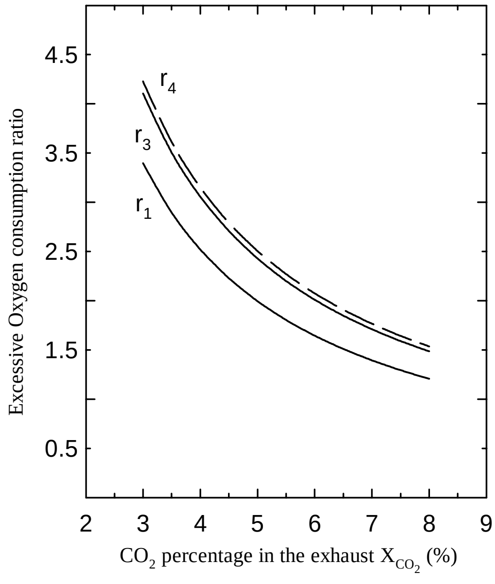

Fig. 1. Variations of calculated r_1, r_3, and r_4 parameters with CO_2 percentage X_{CO2} in the exhaust gas.

However, this huge attendant gas in the furnace, absorbs heat, which subsequently is dissipated outdoors via stack. The total waste heat rate can be calculated as:

$$\dot{Q}_{was} = \sum \dot{n}_i \; C_{pi} \; \Delta T_a + \dot{m}_w \; L_v \quad (8)$$

So, the ratio of waste/total heat rate can be calculated as:

$$R_{was} = \dot{Q} / \dot{V} Q_v \quad (9)$$

where Q_v, the higher heating value of natural gas has be taken 40MJ/m^3.

Generally the excessive oxygen (and so the air) consumption ratio (coefficient) depends on heater power and geometry of the furnace and increases mainly with vertical stack length and its diameter. In practice "stack length" is the most common variable and varies in the range of 3-5m in single floor houses.

In this work a conventional domestic gas heater with maximum 7200W heat power has been used. It has been equipped with a 5.5m vertical, galvanized iron stack with 10.5cm diameter. The exhaust temperature has been measured at the stack exit T_{sout}, while the CO_2 percentage X_{CO2} measured by a Varioplus gas analyzer. This procedure has been repeated for different stack lengths and variations of the exhaust temperature and CO_2 percentage versus stack length have been depicted in Figs. 2.a) and 2.b) respectively. This experiment indicates that, the excessive oxygen consumption ratio is an increasing function of stack length in the range of 1.4-2.9 .

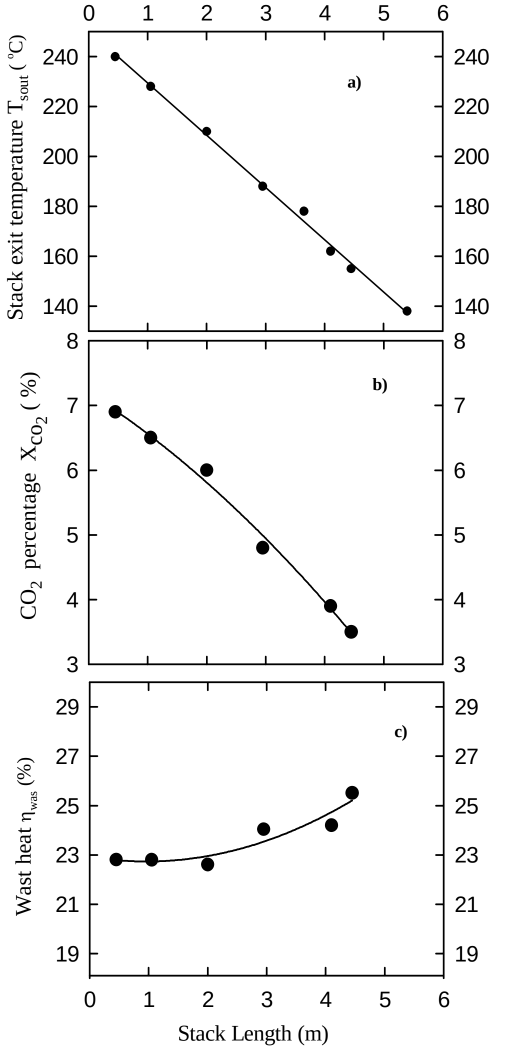

Fig. 2 Variations of: a) exhaust temperature T_{sout} measured at the stack exit, b) CO_2 percentage X_{CO2} in the exhaust gas measured by a Varioplus gas analyzer, and c) the calculated waste/total heat ratio (×100), versus stack length.

The total waste heat rate has been calculated according to equation (8), for different stack lengths and the calculated waste/total heat ratio (×100) as a function of stack lendth measured at 20 ± 1 °C ambient temperature have been depicted in figure 2. c).

The interesting fact is that, despite the longer stack reduces exhaust temperature significantly, but the waste heat enhances due to increment in the excessive air entering furnace, although the damper gate has controlled it to some extend. However, it can be deduced that 25 % of total heat power is dissipated outdoors via stack exit, where the stack length varies in the range of 3-5 m as it is the situation in the buildings applications.

3. DESIGN AND DESCRIPTION OF WATER HEATER

The designed water heater consists of two concentric tube with 1m high made of 0.75-1mm thick galvanized iron sheets. This parallel-flow, convective heat exchanger has been designed as a waste heat recoverer of a 10kw domestic gas heater. Assuming the apparatus can utilize maximum 15% of total heat power via cooling the exhaust gas from 200 °C down to 70 °C while the water temperature be 20 °C and r_1 parameter be equal to 2.2. So the average temperature difference of exhaust gas and the inner wall of the apparatus is 115 °C. A rough thermodynamics calculation [12] shows that the area of the inner tube should be equal to 1.5 m^2, so; it has been designed and fabricated in the form of a "gear-shaped" cylinder, but outer tube is a simple cylinder with 50cm diameter. It's water capacity is 155 lit measured by a vessel gauge and Figs. 3 a), and b), show its side, and top views respectively. There is a 85cm high and 19cm diameter divider tube inside the gear-shaped one, which distributes the hot exhaust towards furrows. There is also a 90cm high and 10.5cm diameter tube inside the divider, and a thermostatic shutter is connected to it's upper end. The shutter is opened at the adjustable temperature and allows hot exhaust flows outdoors directly when the water temperature excides the adjusted value. The apparatus has been covered by 3cm thick glass wool for thermal isolation.

4. EXPERIMENTS

Here the potential of waste heat recovery is studied practically. In this work a domestic gas heater with 5.2(min) -7.2(max) kW heat power has been used. Its outlet was connected to outdoors via an "L" bow and a 3m long vertical galvanized iron pipe (with 10.5cm diameter and 0.3mm thickness). The water heater (apparatus) has been connected to the stack exit on the roof while the gas heater was indoors. It is filled of 14-15 °C water and the heater turned on. No significant changes of the CO_2 percentage in the exhaust gas has been observed, indicating the extension of life of stack. The exhaust temperature at the inlet T_{in} and outlet T_{out} of the apparatus was measured in the stable conditions with time. The water temperature has been measured by a mercury thermometer with 0.2 °C accuracy which has been inserted in the tank through water outlet passage and positioned at 20cm bellow it. The measured water temperature has been approximately (98%) equal to the averaged temperature in the tank.

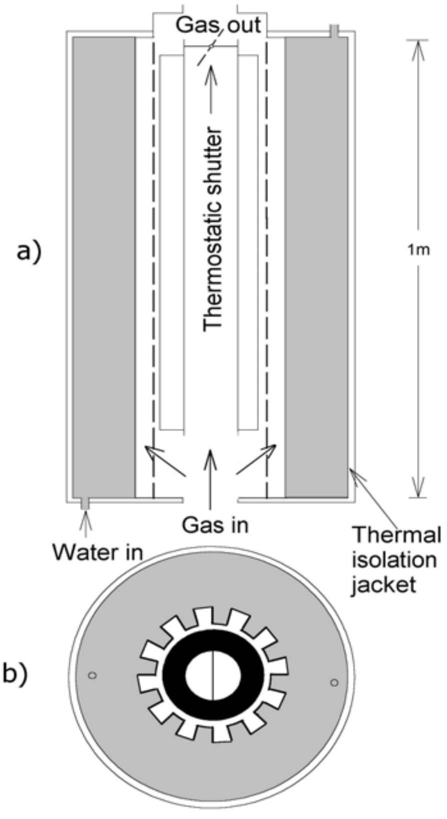

Fig. 3. a) side, and b), top views of water heater apparatus fabricated in this work.

In the first three experiments (tests A,B, and C), the gas heater was set at the maximum power (7200W). In Test A the averaged exhaust temperature measured at the inlet $\bar{T}_{in}$ was 183.5 °C. The variations of water temperature measured with time and the results have been depicted in Fig. 4 (diamond symbols). In the second experiment (Test B), the inlet temperature was lowered to 158 °C (on the average) via indoors ventilation around stack (by an adjustable fan) and the variations of the water temperature with time has been depicted in figure 4 too (circles). In the third experiment (Test C) this procedure was repeated as the second experiment, but a length of 2m of the stack was replaced by 15cm diameter one. As a consequence the exhaust temperature at the inlet was lowered to 140 °C (on the average) and the results has been depicted in figure 4 (triangular up).

In the subsequent experiments (tests D,E, and F) the gas heater was set at the minimum power 5200W. The forth (Test D), fifth (Test E) and sixth (Test F) experiments was carried out in the same manner as A, B and C tests, respectively and the results have been depicted in Fig. 5.

A typical variations of inlet T_{in} and outlet T_{out} exhaust temperature as a function of time t has been depicted in Fig. 6 for test C. As seen the outlet gas temperature follows the water temperature.

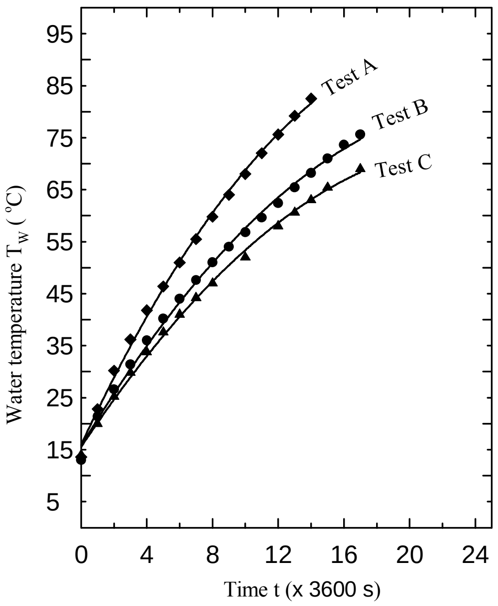

Fig. 4. Experimental results (symbols) of heating tests of water heater apparatus for 7200W gas heater power but different inlet exhaust temperatures . The experimental results of each test were fitted by second order linear regression analysis (solid curves).

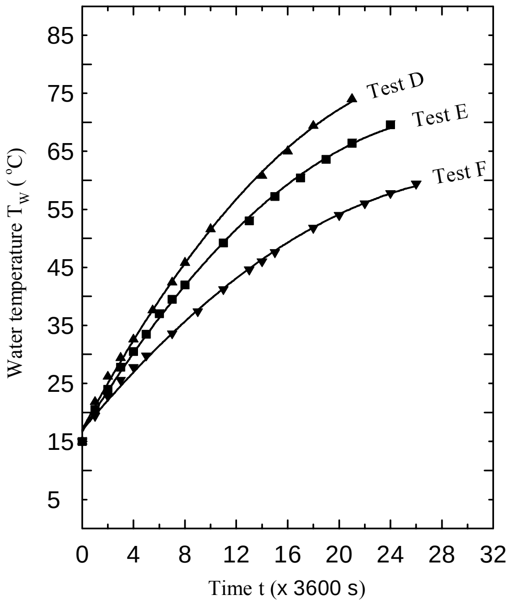

Fig. 5 Experimental results (symbols) of heating tests of water heater apparatus for 5200W gas heater power but different inlet exhaust temperatures. The experimental results of each test were fitted by second order linear regression analysis (solid curves).

A typical variations of inlet T_{in} and outlet T_{out} exhaust temperature with water temperature has been shown in Fig. 7 for test F.

The heating tests specifications of the water heater under study have been compiled in table 1 for comparison.

After a heating test, the inlet and outlet exhaust passages of the water heater was sealed by thermal isolation pads and the cooling experiment was carried out to evaluate the quality of thermal isolation jacket, and the variations of water temperature (circles) and ambient (squares), have been depicted in Fig. 8. A second order linear regression analysis has been applied to cooling test (solid curve) while the ambient has been weighted with a straight line.

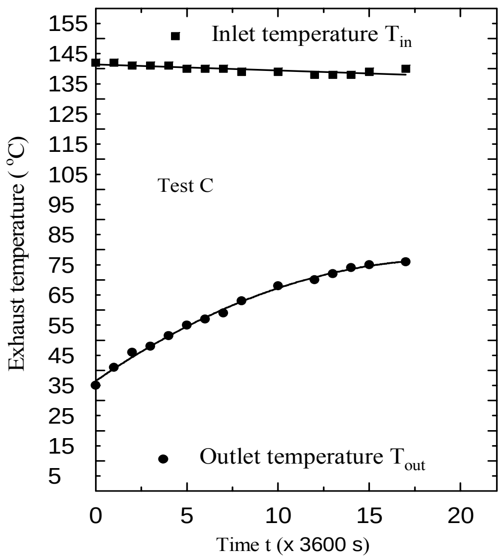

Fig. 6. Variations of the inlet T_{in} , and outlet T_{out} , exhaust temperature versus time t measured in test C.

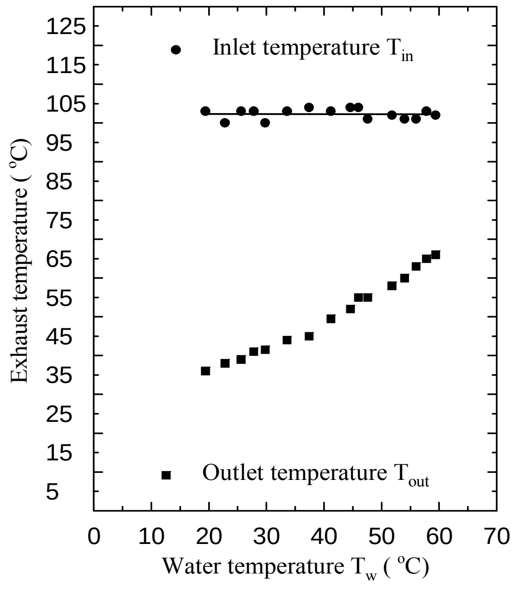

Fig. 7. Variations of the inlet T_{in} , and outlet T_{out} , exhaust temperature versus water temperature T_w measured in test F.

Table 1. Heating tests specifications of water heater under study.

Test	H_{gh} (W)	$\bar{T}_{in}$ (°C)	$\bar{T}_a$ (°C)
A	7200	183.5	14.16
B	7200	158	13.2
C	7200	140	10.1
D	5200	141	4.3
E	5200	121.8	2.56
F	5200	102.5	7.6

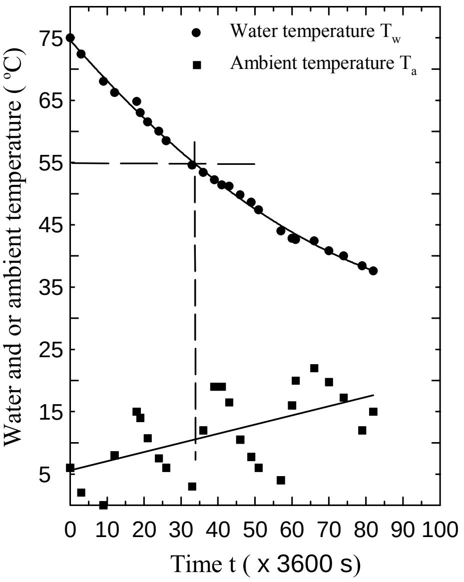

Fig. 8 . Variations of water temperature (circles) and ambient (squares), with time for a cooling test. In this test the inlet and outlet exhaust passages have been sealed thermally.

5. RESULS AND DISCUSSIONS

The experimental results of heating tests (symbols) shown in Figs. 4 and 5, was fitted very well by second order linear regression curves as shown. The efficiency of heat recovery can be evaluated by effective heating power as:

$$H_{eff}\,(T_w)=M_{wh}C_w\,\frac{dT_w}{dt} \tag{10}$$

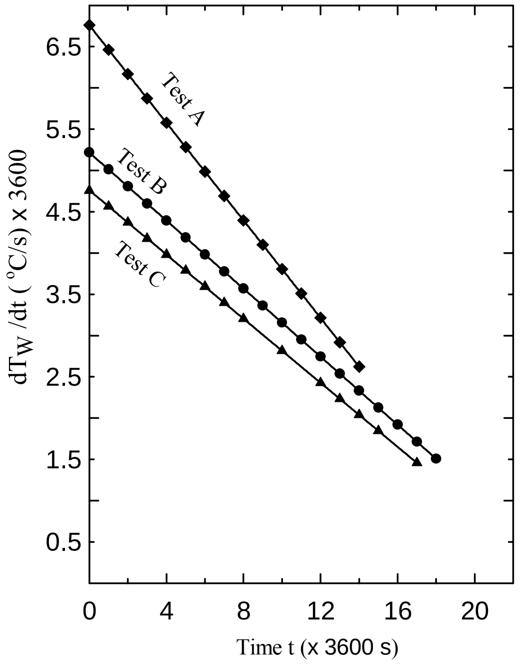

Fig. 9 . Variations of dT_w /dt with time t in heating tests of water heater apparatus for 7200W gas power. The stright lines are corresponding to curves in Fig. 4.

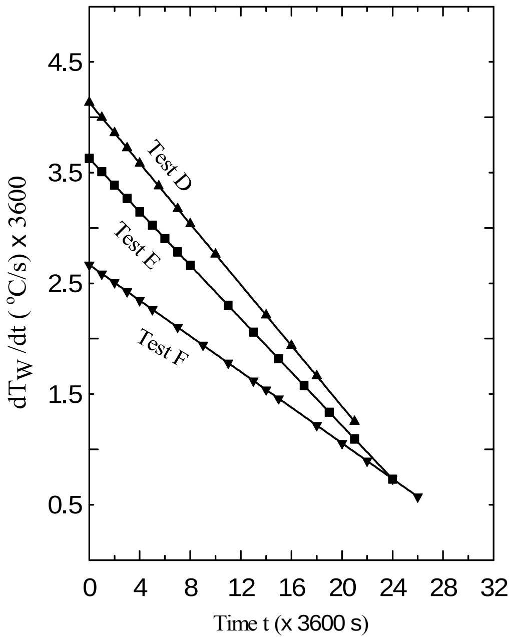

Fig. 10 . Variations of dT_w /dt with time t in heating tests of water heater apparatus for 5200W gas power. The stright lines are corresponding to curves in Fig. 5.

The dT_w /dt variable which is a function of water temperature T_w was calculated for each curve using the derivative of the extracted second order equation as mentioned before and the results have been shown in Figs. 9 and 10 corresponding to exprimental results of Figs. 4, 5 repectively. Then calculated results for the effective heating power versus water temperature have been depicted in figures 11 and 12 corresponding to Figs. 4, 5 respectively. As expected the effective heating power increases with exhaust temperature T_{in} and or gas heater power H_{gh} but decreases with water temperature. The reduction in the thermal efficiency at the higher water temperatures is related mainly to the quenching in heat transfer process due to reduction in the temperature difference of the water and exhaust gas as it is obvious in Fig. 7. Moreover, thermal dissipation from outer tube of the apparatus becomes important at higher water temperatures.

The quality of thermal isolation jacket has been evaluated by a second order linear regression analysis applied to experimental results of cooling test (Fig. 8) and the variations of the calculated thermal dissipation of water heater H_{tdwh} versus water temperature has been shown in Fig.13. As expected thermal dissipation of the apparatus becomes significant at higher water temperatures and or colder weather, so this limits its efficiency especially in lower exhaust temperatures and heater powers. A discerning consideration of the dashed lines shown in Figs. 8 and 13, implies that for a wintry weather (with 45 °C temperature difference of water and ambient) the thermal dissipation is about 90W. So, a partial improvement in thermal isolation does promote the efficiency of the appliance significantly.

For evaluating the efficiency of this apparatus, the effective heating power at the desired water temperature 45 °C has been determined (see the intersections of vertical dashed lines and curves, in Figs. 11 and 12). Moreover the thermal efficiency of the apparatus (at $T_w = 45$) has been calculated for the aforementioned tests according to:

$$\eta_{wh}(45) = 100 \times H_{eff}(45) / \dot{V} Q_v \tag{11}$$

and the results have been compiled in Table 2 for comparison. The thermal efficiency of the A(45) indicates that the apparatus could utilize 13% of total heat which is wasted. The enhancement in thermal efficiency of water heater at D(45) relative to B(45) and C(45), is related to increase of excessive oxygen consumption parameter due to lower gas heater power as mentioned in section 2.

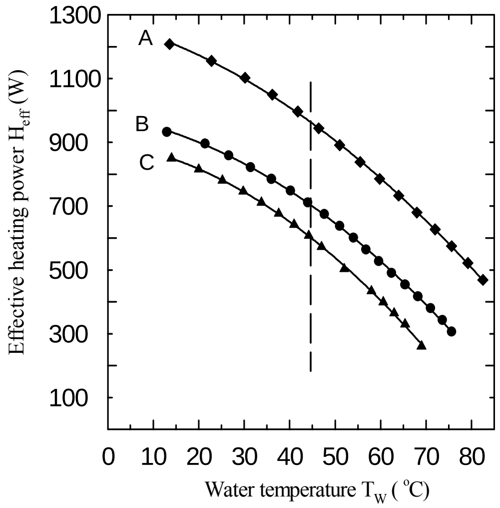

Fig 11. **Variations of calculated effective heating power, versus water temperature for the corresponding heating tests shown in Fig. 4. The intersections of the vertical dashed line and curves, is a measure of thermal efficiency at desired water temperature, 45 °C.**

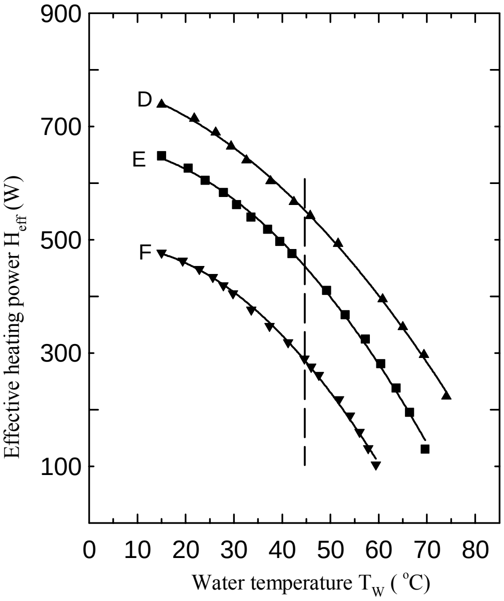

Fig. 12. Variations of calculated effective heating power, versus water temperature for the corresponding heating tests shown in Fig. 5. The intersections of the vertical dashed line and curves, is a measure of thermal efficiency at desired water temperature, 45 °C.

However, a simple calculation shows that the appliance could recover 25MJ heat daily in the worse conditions (Test F), and this is sufficient for warming up 200lit water from 15 to 45 which is of great interest in building applications.

Table 2. The calculated effective heating power H_{eff} (45) and thermal efficiency ç$_{wh}$ (45) of the appliance at desired water temperature (T_w = 45 °C), for different heating tests.

Test	H_{gh} (W)	H_{eff} (45) (W)	η_{wh} (45) (%)
A(45)	7200	960	13.33
B(45)	7200	700	9.72
C(45)	7200	607	8.43
D(45)	5200	550	10.57
E(45)	5200	450	8.65
F(45)	5200	290	5.57

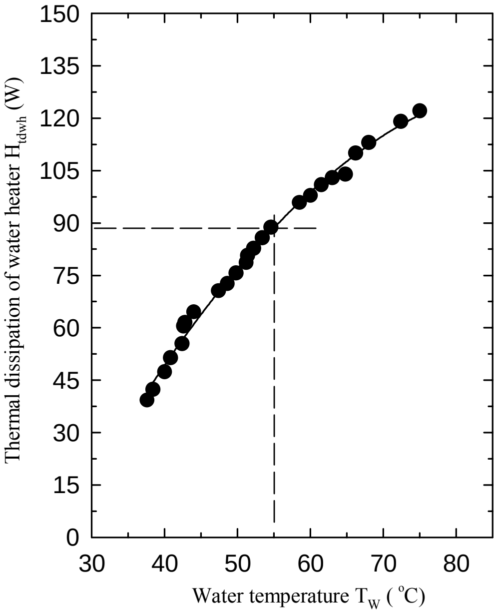

Fig 13. The variations of the calculated thermal dissipation of the apparatus H_{tdwh} with water temperature , for the cooling test shown in figure 8.

6. ECONOMICS

From ecoonomical poit of viwes, the instalation and use of the water heater system higly depends on the fabrication and maitenance charges. Here, in order to evaluate the benefits, a rough estimation of costs and profits is made. The total galvanized iron plate with 4 m^3 and maximum 2mm thickness costs 60$. The exhaust divider and exit tubes charges tottaly 10$ including their constraction fees. The thermostatic shutter and isollation jaket and other fixing parts costs 30$. The construction charges in mass production is estimated 60$. Assuming that, selling profits and instalation chages be 40$, the total price is estimated 200$.

On the other hand, the average volume consumption of natural gas for heating of a 160m^2 single floor house in the Yazd sity with a mild winter (the average temperature in January was about 5 °C) recorded 1900±100m^3 per year for 8 sample houses. Taking that the appliance can utilize just 7% of the total consummed gas for heating water and assuming that, the world price of natural gas in witer period be 0.35\$/m^3, one can figure out that the payback time will be 4 years much shorter than its lifetime which is estimated 10 years.

7. CONCLUSION

In order to utilize the domestic gas heater exhaust energy, a parallel-flow, convective heat exchanger has been fabricated for water heating in buildings applications. This device is mounted on the roof, connected to the stack and the hot exhaust flows through its inner gear-shaped tube. The heat recovery potential of the appliance has been tested for 5.2 and 7.2kW gas heater powers and different exhaust temperatures in the range of 100-185 °C. The results indicate; at the desired water temperature 45 °C, the effective heating power enhances in the range of 290-940W proportional to the exhaust temperature and or gas heater power. The apparatus could utilize up to 13% of total heat which is wasted, and it is fit to low grade, domestic gas heaters which are widely used and can supply hot water for buildings applications. Economical considerationns reveals that the payback time of installation this appliance is 4 years much shorter than its lifetime.

ACKNOWLEDGMENT

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NOMENCLATURER

C_{pi}	molar heat capacity at constant pressure of ith gas in the exhaust (J/mol °C)
C_w	water heat capacity (J/kg °C)
ΔT_a	temperature difference between stack exit and ambient (°C)
H_{eff}	effective heating power of the apparatus (W)
H_{gh}	gas heater power (W)
H_{tdwh}	thermal dissipation of water heater (W)
L_V	vaporization latent heat of water (J/kg)
M_{wh}	the mass of water in thewater heater tank (kg)
$\dot{m}_w$	produced water mass rate (kg/s)
$\dot{n}_i$	mole rate of ith gas in the exhaust (mol/s)
Q_v	higher heat value of natural or fueled gas (J/m^3)
$\dot{Q}_{was}$	waste heat rate (W)
r_1	excessive oxygen consumption ratio of methane
r_3	excessive oxygen consumption ratio of propane
r_4	excessive oxygen consumption ratio of butane
R_{was}	the ratio of waste/total heat rate
t	time (s)
T_a	ambient temperature (°C)
$\bar{T}_a$	averaged ambient temperature (°C)
T_{in}	exhaust temperature at the inlet of water heater (°C)
T_{out}	exhaust temperature at the outlet of water heater (°C)
T_{sout}	exhaust temperature at the stack exit (°C)
$\bar{T}_{in}$	the averaged temperature of exhaust gas at the inlet of water heater (°C)
T_w	water temperature in the water heater tank (°C)
$\dot{V}$	natural or fueled gas consumption volume rate (m^3/s)
X_{CO2}	CO_2 percentage in the exhaust gas (%)

Greek symbols

η_{was}	the ratio of waste/total heat rate × 100 (%)
η_{wh}	thermal efficiency of water heater apparatus (%)

Subscripts

gh	gas heater
wh	water heater apparatus
was	waste
w	water

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