PROTOTYPE OF A HEAT RECOVERY FOR COOLING OF GASES FROM INCINERATION OF HAZARDOUS WASTE

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ABSTRACT

This paper presents the stages of development and construction of a prototype of a shell and tube heat recovery for reuse heat energy of the products generated by combustion of hazardous waste incinerator class I. The performance and energy recovered by this system were calculated. It was transported the values found for a typical plant for the incineration of 1,000 kg h^{-1}. Thus, to preheat the combustion air and drying the waste was obtained a reduction in the consumption of LPG 46 and 45%, respectively. Considering the complexity of the process, it was found that the preheating system is simpler and can be deployed in a shorter time and lower cost when compared to a drying residue.

Keywords: heat recovery, preheating air, drying waste, incineration.

NOMENCLATURE

A	total surface area, m^2
C_{min}	minimum rate of heat capacity, W/K
C_r	ratio of heat capacities
D_o	diameter of the outer surface, m
D_i	diameter of the inner surface, m
E_{cm}	energy saved in a month, R$
h_i	coefficient of heat transfer by internal convection, W/m^2 K
h_{LV}	latent heat of vaporization of water, J/kg
h_0	coefficient of heat transfer by external convection, W/m^2 K
H	enthalpy of the air outlet of the heat exchanger, W
H_m	produced Enthalpy, J/month
k	thermal conductivity, W/m K
NUT	number of transfer units
P_{GLP}	LPG price, R$/kg
PCI_{GLP}	net calorific value of LPG, J/kg
PCI_R	net calorific value of the waste, J/kg
PCU	useful calorific value of the waste, J/kg
$q_{máx}$	maximum rate of heat
q_p	predicted rate of heat between the hot and cold fluids, W
q_R	actual rate of heat between the hot and cold fluids, W
$R''_{f,i}$	internal fouling factor, m^2 /W
$R''_{f,0}$	external fouling factor, m^2/W
MWS	medical waste service
$T_{c,i}$	temperature of cold fluid inlet, K
$T_{c,o}$	temperature of cold fuid outlet, K
T_{coP}	predicted temperature of cold fluid outlet, K
T_{hoP}	predicted temperature of the hot fluid outlet, K
U	overall coefficient of heat transfer, W/ m^2 K
x_{H_2O}	mass fraction of moisture

Greek symbols

ε_p	predicted effectiveness
ε_R	actual effectiveness

INTRODUCTION

The problem of solid waste is a subject of global interest, and has been treated as a priority, together with the problems related to water and the environment, Braga et al. (2006). According to França et al. (2009), population growth and intense urbanization, associate with the excessive consumption of natural resources, are the ideal combination for the environmental disequilibrium, phenomenon that characterizes the present era. Brazil is not an exception to this world, and in most urban areas the disposal of municipal solid waste is inadequate. It is usual to check the dumping of solid waste without criteria in the environment, affecting the quality of soil, air and water.

Discharges of medical waste service (MWS) cause severe environmental impact if not properly treated. These characteristics have toxic or infectious, so the stock, handling, transportation and disposal of such waste, requires a procedure for handling and special handling. According to Jangsawang et al. (2005), historically, most of the MWS were discarded in landfills or burned in rudimentary incinerators with inadequate controls. Currently there are several treatment technologies such as incineration, autoclaving, chemical disinfection, disinfection gas, and microwave irradiation. However, the use of these technologies is still limited. Many of these technologies do not reduce significantly the mass of all the waste and do not always achieve the total disinfection and do not completely destroy toxic chemicals highly dangerous. Available technologies as incineration has been the most effective in destroying toxic components and reducing the mass and volume of these wastes.

As Shaaban (2007), the incineration of MWS is a process technically and economically viable, particularly in developed countries. The technique of incineration destroys any kind of organic carbon and reduces by 80-95 % the mass of material. The heat of combustion can be recovered and used to generate steam, produce hot water or dry other wastes with low calorific value Mckay (2002). Different categories of MWS can be treated, such as infectious agents, pathogenic waste, waste containing blood, needles, syringes, contaminated animal carcasses, waste from surgery and autopsies procedures, pharmaceutical wastes, dialysis wastes, disposal of equipment medical and biological waste and chemicals in general.

According to CONAMA resolution number 358 of 2005, the residues with the possible presence of biological agents that, by their characteristics of higher virulence or concentration, may be at risk of infection, should undergo treatment processes to reduce microbial load. The solid wastes are classified according to NBR 10004 (Brazilian Association of Technical Standards - ABNT, 2004), waste class I and class II, according to his dangerousness. The wastes class I are hazardous waste from the medical service and the majority of industries. These residues can not be sent to landfills common and must undergo special treatment to reduce the environmental and health impact. In this case, the incineration process is indicated in the treatment of these solid wastes. According to NBR 11175 (ABNT, 1990), the incineration process is a high temperature oxidation that destroys or reduces the volume or retrieves materials or substances. The excess of air must be used to ensure destruction efficiency by minimizing the formation of products of incomplete combustion. It is recommended to keep the oxygen standard concentration greater than 7%.

According to Stehlik (2006), recovery of heat in a thermal process using various types of waste, besides the importance of biomass combustion, it is of great importance. Therefore, the development of a equipment for utilization the energy contained in flue gases from the thermal treatment is one of the key points in the development of incineration technology, particularly in the reduction of operating cost. The heat recovery is one of the most viable subsystems to consider in the incineration of waste. The current incineration processes are increasingly subject to environmental laws and regulations while seeking maximum energy generated by this process. It is possible to determine the amount of energy generated and re-used in any type of heat exchanger using enthalpy balance.

Given the above and the existence of a high demand for incineration plants projects, mainly for treatment of MWS, it is necessary to research a system for recovering heat generated in waste incineration plants. Therefore, this study aimed to develop and build a prototype of a heat recovery and propose how it will be reused the recovered energy.

METHODOLOGY

The project was carried out at the Federal University of Viçosa (UFV), in the area of Energy, Department of Agricultural Engineering. To develop the heat recovery were considered operating conditions of the MWS pilot incinerator of Laboratory of Energy at the Department of Agricultural Engineering of Federal University of Viçosa. It was developed a shell and tube heat exchanger with one pass in shell, type TEMA E, by presenting a reduced construction cost and a relatively lower pressure drop when compared to other types of shell. Still, for this type of heat exchanger is widely used in industries due to its robustness, ease of maintenance and cleaning, is relatively simple and good adaptability to different operating conditions (Wang and Wen, 2009). It was decided to design the tube bundle as well as the upper and lower heads removable, to allow maintenance, and cleaning or replacement. The fluid flowing inside of the tube bundle are the exhaust gases from the incinerator to have a higher impurity atmospheric air. In this case, is easier to removal the impregnated impurities inside of the tubes by using specific devices in the form of rods. On the other hand, the fluid flowing in the shell side, outside the bundle of tubes, is the atmospheric air.

The initial data, as well as the thermophysical properties of gases and air, for the design of the heat exchanger were obtained through literature reviews, such as Shaaban (2007), Incropera (2008), Çengel (2009), Shah (2003) and design parameters of the pilot incinerator.

Overall coefficient of heat transfer

The surface area of heat transfer was calculated by determining the overall coefficient of heat transfer (U) taking into consideration the thermal resistance of the walls of the tubes.

$$U = \frac{1}{\frac{D_o}{h_i D_i} + R''_{f,i}\frac{D_o}{D_i} + D_o\frac{\ln\left(\frac{D_o}{D_i}\right)}{2K} + R''_{f,o} + \frac{1}{h_o}} \quad (1)$$

The heat transfer coefficients for convection the gas side and the air side, as well as fouling factors on the inner side of the tube and shell side was expressed by Eq. (1) Incropera et al. (2008). It was adopted commercial tubes carbon steel SAE 1020 with outer and inner diameter of 21.05 and 19.05 mm, respectively.

Evaluation of performance of the heat recovery

To evaluate the performance of the heat exchanger, it was used the pilot incinerator of the energy laboratory of the department of agricultural engineering that it was designed with the capacity to incinerate 0.6 kg h^{-1} of waste. It has two chambers, the primary with 14,880 cm ³ and secondary of 9,920 cm ³.

The waste incinerator developed follow all precepts pertaining to the thermal decomposition of waste recommended in standard ABNT NBR 11175. The power of the waste incinerator was performed every 10 minutes with loads of 100 g, packed in bags, the usual way of waste disposal system health. Because of the potential toxicological waste health, it was decided not to use this waste in the research, avoiding contamination of staff. Thus, the waste incinerated was obtained from a simulation of health waste from the gravimetric composition according Ferreira (1999), Smith et al. (2001) and Solomon et al. (2004).

To evaluate the heat recovery, six tests were performed randomly at different times. Each experiment was started after stabilization of the temperature of the combustion chamber, the heating time due to thermal inertia, was approximately 40 min, after started collecting data every five minutes. We measured the temperature of the combustion chamber, the inlet and outlet temperatures of the hot and cold fluids, as well the speeds of these fluids. The power to the load of the incinerator was conducted every ten minutes, the measurements being performed soon after and after five minutes. The total duration of each test, disregarding the thermal inertia, was two hours.

To verify the performance of the heat recovery, it was initially compared the outlet temperatures of the two fluids predicted and measured from the inlet temperatures of the hot and cold fluids. Furthermore, measures using mass flows and entry temperatures of the heat recovery was compared to actual recovered heat rate with the rate of heat recovered predicted, expressed as follows:

$$q_p = \varepsilon_p q_{máx} \quad (2)$$

The number of transfer units is a dimensionless parameter that was used for the analysis and development, (Theodore, 2011), as follows:

$$NUT = \frac{UA}{C_{\min}} \quad (3)$$

Therefore, the maximum rate of heat transfer was calculated by:

$$q_{máx} = C_{\min}(T_{h,i} - T_{c,i}) \quad (4)$$

The predicted effectiveness:

$$\varepsilon_p = \frac{1-\exp\left[-NUT(1-C_r)\right]}{1-C_r\exp\left[NUT(1-C_r)\right]} \quad (5)$$

On the other hand, the actual rate of heat recovered by the cold fluid (air atmosphere):

$$q_R = \dot{m}_c c_{p,c}\left(T_{c,o} - T_{c,i}\right) \quad (6)$$

The actual effectiveness was defined as follows:

$$\varepsilon_R = \frac{q_R}{q_{máx}} \quad (7)$$

$$T_{coP} = \frac{q_p + \dot{m}_c c_{pc} T_{ci}}{\dot{m}_c c_{pc}} \quad (8)$$

$$T_{hoP} = \frac{q_p + \dot{m}_h c_{ph} T_{hi}}{\dot{m}_h c_{ph}} \quad (9)$$

Therefore, the predicted outlet temperature of hot and cold fluids, were calculated by Equations (8) and (9).

Evaluation of the use of energy recovered

To determine the energy recovered it was calculated the gain of enthalpy of the atmospheric air at the outlet of the heat recovery. To determine the total energy contained in the atmospheric air after recovery, was calculated by (Masterton and Hurley, 2009):

$$H = \dot{m}_c c_{p,c} T_{co} \quad (10)$$

To quantify the reduction of energy, LPG, consumed in the combustion process to be returned this heated air to be reused by the burners was taken into account the enthalpy of the exhaust air produced by the stove in a month, taking into account this incinerator operating 24 hours. This total enthalpy is equals the amount of energy in Joules recovered within one month. Therefore, the savings in this period was calculated as the ratio of total enthalpy by calorific value of LPG multiplied by the price of LPG, expressed by:

$$E_{cm} = \frac{H_m}{PCI_{GLP}} P_{GLP} \tag{11}$$

On the other hand, the recovered energy may be used to raise the PCI of the MWS, reusing this enthalpy to heat the air, drying such residues. To do this, it was calculated the amount of energy required for drying 100 g of these residues with moisture content of 20%. The energy required to withdraw all of this moisture was determined by Gonçalves et al. (2009).

$$PCU = -x_{H_2O} h_{LV} + (1 - x_{H_2O}) PCI_R \tag{12}$$

RESULTS AND DISCUSSION

Rate of heat transfer to the cold fluid

The rate of heat transfer to the cold fluid was determined by means of the mass flow measurements of cold fluid from the cold fluid specific heat and temperature differences in the fluid that it has undergone. This means the rate of heat energy recovered by cold fluid heat transfer in this system. This rate or regenerated power can be interpreted as being the energy recovered by time. The values of this energy recovered are shown in Fig. 1.

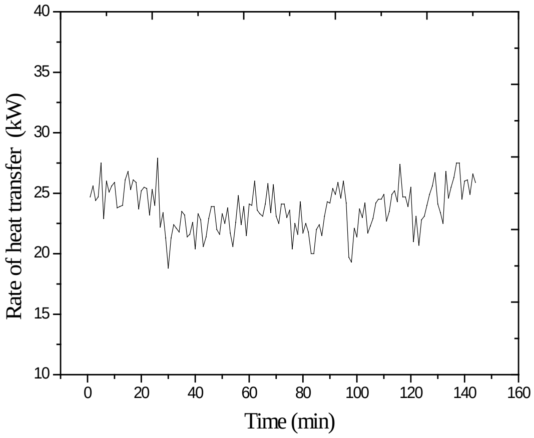

Figure 1. Rate of heat transfer to the cold fluid.

Therefore, the average of the rate of the heat recovered was 23.7 kW, with maximum and minimum values of 18.8 kW and 27.9 kW respectively and standard deviation of 1.8 kW. The coefficient of variation was 7.8%.

Comparison between the predicted and transferred heat rates to the cold fluid

The predicted heat transfer rates were determined according to the maximum possible effectiveness in this area of heat transfer of this heat recovery and the maximum possible rate of heat transfer between two fluids, subjected to these differences of temperature. The comparison result follows in Fig. 2.

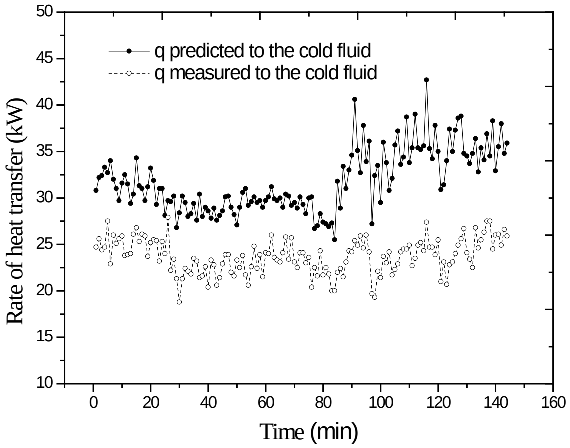

Figure 2. Comparison of rates of heat transfer to the cold fluid predicted and measured.

In this case it can be seen that the rate of heat transmitted to the cold fluid, working fluid, is below of the expected rate of heat. This rate of heat that was not transmitted to the cold fluid is considered thermal loss to the neighborhood that exceeded the boundary of the system. So, this heat loss is considered wasted energy that is not able to turn into work. The lower the energy loss, more efficient will be the system. Another indicator of this comparison is the quantification of how much of this heat exchange system may be subjected to a gain in thermal efficiency. Therefore the difference between the predicted heat rate and the rate of heat exchanged is the amount of potential energy gain of the heat recovery system.

Comparing the effectiveness of the heat recovery and effectiveness predicted

To determine the effectiveness of this heat recovery it was determined the maximum possible rate of heat transfer in this exchanger. This maximum was achieved considering a heat exchanger ideal with infinite length in which the hot and cold fluids would be subject to maximum temperature difference as possible, that is, the temperature difference between the hot and cold fluids. To determine the effectiveness of the predicted heat recovery the ε - NUT method was adopted, NUT is the number of heat transfer units. To determine the overall coefficient of heat transfer, needed to determine the coefficients of heat transfer by convection inside and outside the tube bundle. These being due to the flow of hot and cold fluids. Therefore, the amount of heat transfer is directly related to the Reynolds number of internal tubes and the maximum Reynolds number was calculated when the cold fluid passes through the bundle of tubes, which can be seen in Table 1.

Table 1. Reynolds number, coefficient of heat transfer by convection and overall coefficient of heat transfer.

	Re_D	Re_Dmax	$h_i(Wm^{-1}K^{-1})$	$h_o(Wm^{-1}K^{-1})$	$U(Wm^{-1}K^{-1})$
Average	4,357.0	15,130.7	30.6	156.2	21.3
Minimum	4,018.7	13,354.8	28.0	145.7	19.1
Minimum	5,141.5	16,786.4	35.6	165.5	25.5
Standard deviation	231.1	672.8	1.5	3.9	1.3
Coefficient of variation (%)	5.3	4.4	4.9	2.5	5.9

The calculated average value of NUT was 1.174 and the minimum value was 1.161 and maximum value was 1.191 with a coefficient of variation of 0.578 and a standard deviation of 0.006. The comparison between the predicted and actual effectiveness is shown in Fig. 3 and the values of effectivities and rates in Table 2.

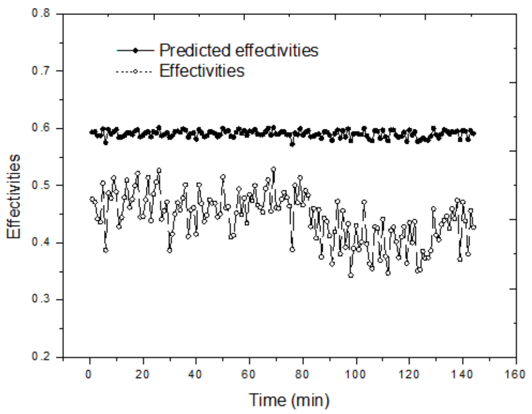

Figure 3. Comparison of the predicted effectivities and effectivities of the heat recovery.

Table 2. Rate of the heat transfer, rate of the predicted heat transfer, predicted effectiveness and effectiveness.

	qp(W)	q(W)	ε_p	ε
Average	31,839.6	23,725.8	0.590	0.443
Minimum	25,509.3	18,830.5	0.572	0.343
Minimum	42,699.5	27,949.9	0.601	0.566
Standard deviation	3,375.1	1,855.7	0.006	0.044
Coefficient of variation (%)	10.6	7.8	1.504	10.020

It can be seen that the predicted effectiveness has a coefficient of variation of 1.054. This small variation is justified because the effectiveness predicted is calculated by the NUT and the ratio of heat capacity rates. Moreover, the effectiveness of the heat recovery takes into consideration the inlet temperatures of the hot and cold fluids, which may be reported as the cause of a greater variation in the results. When comparing the effectiveness with the predicted effectiveness, you can define how it is possible to make the system more efficient. Comparing the effectiveness, it shows that this heat recovery can have 25% of gain of heat transfer efficiency.

Quantification of energy recovered

The average energy recovered by the working fluid in the heat recovery was 23.7 kW. Therefore, this energy can be returned to the burners with the consequence of reducing the consumption of LPG. On the other hand, this energy can be used for drying of these residues to increases the net calorific value before being introduced into the incinerator, resulting in a more efficient incineration plant with regard to operating costs. By analyzing the hypothesis of this recovered energy back to the burners in the form of enthalpy for the combustion air, considering this incinerator working at full capacity in three shifts (24 hours), the energy recovered in a day would be 2,047,680.0 kJ. Energy savings in terms of reduced consumption of LPG in a day's work was calculated as the product of the price of LPG by the ratio of energy recovered by net calorific value. So in a day's work saved would be equivalent to 45.5 kg of LPG, which would reduce operating costs of the plant at R$ 86.45 per day. At the end of the month, allowing for thirty working days would reduce operational cost R$ 2,593.50. Therefore, if the incinerator is operated with the enthalpy recovered returning to the burners, the new mass flow rate of LPG would be 0.00058 kg s^{-1}, the result in a 46% reduction of the consumption of LPG.

On the other hand, this recovered energy can be used for drying waste, increasing the net calorific value of the waste. Therefore, was determined the amount of waste that energy would be able to dry. Knowing that the latent heat of vaporization of water is 2.26 $MJkg^{-1}$ and 20% residual moisture has been calculated the amount of energy required to vaporize moisture contained in this residue. The net calorific value of the waste was calculated as a weighted average (3,905.5 kcal kg^{-1}) less the energy required to remove moisture existing in this residue. Which, is the product of the water content by the latent heat of vaporization of water. Thus, the PCU calculated was 3,033.3 kcal kg^{-1}. It appears then that the energy required for drying one kg of MWS, with such gravimetric composition, is 107.96 kcal or 0.45 MJ. Knowing that this system recovers 23.7 kW and considering this incinerator working at full capacity in three shifts, 24 hours a day, the recovered energy for a day would be 2,047.68 MJ. So on a day of operation recovered energy would be able to 4,550.4 kg of dry waste. At the end of the month allowing for thirty days of work energy recovered would be able to dry the equivalent of 136,512.0 kg of waste, which would result in a reduction of fuel consumption, therefore the incineration plant would reduce operating costs becoming more sustainable. By analyzing this incinerator use only dry waste, it was calculated a new fuel consumption. Therefore the new LPG mass flow rate was 0.00106 kg s^{-1}, resulting in a reduction of the LPG consumption of 2%. It was observed that preheating the combustion air showed a greater reduction in the consumption of LPG, 46%. To be compared with the drying system of waste presented a reduction of 2%. Considering the complexity of processes, it is found that the preheating system is simpler and may be implemented in less time and at lower cost compared to a system for drying waste. Note that the drying residue decreased by only 2 % due to the flow of the waste mass to be very low in the pilot incinerator. On the other hand, the calorific value of the waste increased by 29 %. Transporting the values found in this study to check the alternative use of recovered energy for a typical plant for the incineration of 1,000 kg h^{-1}, where it spends on average of 5 kg of waste per kg of LPG and an operating cost R$ 0.70 kg^{-1}, the options for reuse and energy equivalents are presented in Table 3.

Table 3. Alternatives to the use of recovered energy in a typical incineration plant with a capacity of 1,000 kg h^{-1}.

Alternatives of LPG consumption	LPG consumption (kgs^{-1})	Reduction of energy (%)	Estimated Operating Cost (R$$kg^{-1}$)
Inceneration without recovery	0.0560	0	0.70
Preheating the combustion air	0.0302	46	0.38
Drying the residue	0.0308	45	0.39

Therefore, the results of two options for using the recovered energy in terms of operating costs of a typical incineration plant, it can be seen that the two options influence in reducing the fuel consumption. The option that has a better cost and benefit was to preheat the combustion air. Reducing operational cost R$ 0.32 per kg of waste incinerated, resulting in an increase in profit and making this incineration plant more competitive.

CONCLUSIONS

The energy recovered by this system, combustion air preheating and drying waste, led to an equivalent reduction of consumption of LPG 46 and 45%, respectively. Considering the complexities of processes, it has been found that the preheating system is simpler and able to be implemented in less time and at lower cost when compared to a system for drying waste.

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