



Reuse of Recovered Waste Tail-Gas in a Full-Scale Furnace

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ABSTRACT

Recovery and reuse of waste energy to reduce fuel dependence on petroleum fuel, and to alleviate emissions of contaminants is becoming an important policy for managing energy and the environment. In the study, the waste tail gas emitted from the various petrochemical unit operations is recovered and reused as a replacement of natural gas (NG) to fuel furnace and boiler. On-site experimental results show that replacing natural gas (NG) by the recovered tail gas (RTG) from some petrochemical processes saves 24.6% of fuel costs and reduces 53.0% of CO₂ emissions. On the other hand, if the natural gas (NG) in a mixed fuel containing both natural gas and fuel oil (NG/FO) is completely replaced by RTG, the resulting RTG/FO or RTG/NG/FO fuel mixtures saves 19.5% of fuel costs and reduce 30.0% of pollution emissions. Thus, from the viewpoint of the overall economics and sustainable energy policy, managing and recovering the energy contained in RTG assists in reducing energy consumption by raising the overall thermal efficiency. The conclusion made in this paper is expected to provide a useful technology that can be developed by industrial nations for raising energy efficiency.

Keywords: Energy Recovery; Carbon dioxide; Furnace.

INTRODUCTION

In recent decades, the global economic prosperity has caused new levels of energy demand (Hu and Kao, 2007; Bhaskar and Mehta, 2010; Wu *et al.*, 2010) with more vigorous limitations on carbon dioxide emissions (Hennicke and Fishedick, 2006; Ning and Sioutas, 2010). The measures proposed for alleviating the energy shortage and environmental problems depend largely on cost-effectiveness (Lund, 2007; Choi and Jo, 2011); these measures need to be implemented by integrating energy policy with environmental management for achieving sustainable development (Hu and Kao, 2007; Vega *et al.*, 2010; Ruttanachot *et al.*, 2011). Most methods currently implemented emphasize reducing energy consumption, improving energy efficiency, and developing alternative energy resources (Lund, 2007; Ozalp and Hyman, 2006; Dincer and Rosen, 1999; Thollander *et al.*, 2007) in order to alleviate dependence on fossil fuels and

the adverse impact on environment (Bari *et al.*, 2011; Chen *et al.*, 2011). New equipment and technology are needed (Xue and Aggarwal, 2003; Barroso *et al.*, 2004; Lunghi and Burzacca, 2004) for improving energy efficiency, developing alternate energy resources, strengthening energy management, renovating equipment with better efficiencies, and recovering waste energy (Lunghi and Burzacca, 2004; Ptasinski *et al.*, 2006). For instance, in the waste recycling industry, scrap iron is recycled to reduce the demand for more energy-intensive virgin materials (Holmgren and Henning, 2004). In the steel industry, replacing natural gas partially with recovered waste blast furnace gas that contains 28% carbon monoxide, and 72% nitrogen can lead to reducing natural gas consumption (Bojic and Mourdoukoutas, 2000), improving heat recovery rate, lowering scrap preheating temperature, and reducing dust emissions (Worrell *et al.*, 2001). The olive oil industry recovers energy for reducing adverse environmental impact and achieving sustainable waste disposal (Caputo *et al.*, 2003).

Recovering waste energy or waste materials is expected to help with more environmentally friendly waste management practices (Marchettini *et al.*, 2007). In a previous paper published by the authors, the reuse of waste fuel gas recovered from a petroleum refinery plant was tested using

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a full-scale medium-pressure boiler and a high-pressure cogeneration boiler. The results show that for the medium-pressure boiler with 50–70% loading, $4.8\text{--}8.0 \times 10^6$ m³/year of natural gas can be saved, and $1.8\text{--}3.0 \times 10^4$ t/year of carbon dioxide emissions can be reduced. For the high-pressure boiler with 50–70% loading, savings of natural gas consumption is $7.7 \times 10^6\text{--}1.3 \times 10^7$ m³/year, and carbon dioxide emission reduction is $1.3\text{--}2.2 \times 10^4$ t/year (Lee et al., 2006; Hsieh and Jou, 2007; Lee et al., 2007; Jou et al., 2008a, b).

The tail gas emitted from some petroleum refinery unit processes, i.e. residue desulfurization, residue cracking, olefins conversion, distillation, desulfurization, and isomerization, contains valuable hydrogen-rich fuel components such as CH₄, C₂H₆, C₃H₈, C₃H₆, i-C₄, i-C₅, H₂S, and H₂O(g). Separating these components from the waste gas requires expensive capital and operational costs, and hence, the current practice is to burn the tail gas in a waste gas incineration tower. However, if the heat energy contained in the waste tail gas is recovered and reused directly (Fig. 1), the objective of reducing energy consumption, pollution emissions, and energy cost can be achieved.

The objectives of this study are: (1) observing the influence of hydrogen content in the fuel on the flame appearance, and (2) studying the thermal efficiency and environmental benefits of replacing natural gas (NG) in the traditional fuel, which may include only natural gas (NG) or mixture of natural gas and fuel oil (NG/FO), to power the heater furnace of an on-site distillation unit.

EQUIPMENT

Energy Reuse Equipment

Burners with co-axial double-ring (45 cm in length) jet spray (inner and outer diameters are 3 mm and 4 mm, respectively, for the inner ring, and 9.4 mm and 14 mm, respectively, for the outer ring) were used so that the fuel jet leaving the nozzle is a fully-developed laminar flow. The fuel stream velocity was maintained constant at 16 cm/s. Methane gas spiked with hydrogen was used to study the influence of hydrogen content on flame formation and appearance. The flame length, appearance and stability were observed using fuels of various volumetric ratio of hydrogen to methane (H₂/CH₄), i.e. H₂/CH₄ = 0/100% (pure CH₄), H₂/CH₄ = 30/70% (30% CH₄ replaced by H₂), and H₂/CH₄ = 50/50% (50% CH₄ replaced by H₂).

Additionally, this research was carried out using an on-site heating furnace and boiler currently operated in a petrochemical plant. The furnace with the pre-heating unit was selected to study the benefits of reusing the recovered tail gas (RTG) on energy consumption and carbon dioxide emissions. Both the heating furnace and boiler are equipped with an internal heat exchanger to pre-heat the influent fuel. The pre-heating operation depends on controlling the emission window and the entrance baffle that regulates the fresh air for adjusting the pressure difference between the air inside and outside the furnace so that the fuel is completely combusted in the furnace. Hence, the fuel composition influences the thermal efficiency of the

furnace significantly. As shown in Fig. 2, the experimental system has two furnaces; each is equipped with 12 multi-port burners that consist of 5 nozzles for burning gaseous fuel (Ko et al., 2005). The natural gas (NG) fuel contains on the average (in volume) 90.8 mol% of CH₄, 6.0 mol% of C₂H₆, 2.4 mol% of C₃H₈ and 0.3 mol% of C₄H₁₀ with 9,700 kcal/m³ of average heat, whereas the recovery tail gas (RTG) contains 12.1 mol% CH₄, 9.0 mol% of C₂H₆, 7.0% of C₂H₄, 4.3 mol% of C₃H₈, 3.1% of C₄⁺, 0.5% of C₅⁺, 0.2% of C₆⁺, 62.0% of H₂, and 170 ppmv H₂S with 5,800 kcal/m³ of average heat.

Energy Reuse Methods

The two fuel mixtures, i.e. RTG/NG (a mixture of recovered tail gas, and natural gas) and RTG/NG/FO (mixture of recovered tail gas, natural gas, and fuel oil), were burnt in two separate furnaces. The system burning RTG/NG/FO was tested using three influent volumetric RTG/NG/FO ratios, i.e. 0/50/50 (original fuel mixture), 25/25/50 (50% NG replaced by RTG), and 50/0/50 (all NG replaced by RTG). The volume of RTG consumed was recorded every hour for 360 consecutive hours at the fuel inlet for each RTG/NG or RTG/NG/FO ratio when the plant-scale distillation unit was fully operated. For safety reasons, RTG was slowly added to the furnace fuel stream with an Automatic Combustion Control (ACC) for adjusting the fuel input based on the temperature of the fluid emitted from the furnace. When the exit fluid temperature changes, the ACC system automatically adjusts the flow rate of fuel into the furnace so that a constant pre-selected temperature can be maintained for the hot fluid leaving the furnace. A portion of the emitted hot flue gas was used to raise the temperature of the incoming air so that a higher average air temperature can be maintained in the furnace. The emitted flue gas was continuously monitored using an on-line Continuing Emission Monitor System (CEMS) (E.S.A. MIR 900) with 5.9% accuracy, 95% confidence level, and $\pm 2^\circ\text{C}$ temperature error. Monthly calibration of CEMS was done using A704.03C for CO, NIEA A411.72C for NO_x, NIEA A442.70C for O₂, and NIEA A415.70A for CO₂. This on-line Continuing Emission Monitor System (CEMS) system had been calibrated before it was used, and was recalibrated every 14 days with analytical grad gas samples. Temperature was measured with a thermocouple (K-Type manufactured by Reotemp Co.) that has an error of 0.3% on the full scale; pressure measurement was done with a bourdon tube manufactured by Ashcroft Co. (error is 0.3% on the full scale).

RESULTS AND DISCUSSION

Energy Recovery Management

The recovered tail gas (RTG) comes primarily from the residue desulfurization unit and the residue cracking unit. For other units, e.g. olefins conversion unit, hydro-treating desulfurization unit and isomerization unit, the tail gas is firstly recycled back to the processing unit, only the excess is sent to a fuel recovery system. The fuel recovery system pressure is maintained at 2.6–3.0 kg/cm² by controlling the

PIC-A valve (Fig. 1). When the system pressure is higher than a pre-set value of 2.6 to 3.0 kg/cm², the PIC-B valve is activated to discharge the excess fuel gas into a waste gas incineration tower in order to maintain the pre-set pressure in the recovery system for supplying the make-up fuel to the distillation, high and medium-pressure boiler, sulfur recovery and normal paraffin units. Although the RTG has complicated compositions and contains hydrogen gas varying from 40 to 80 mole% with lower heat values ranging from 4.8×10^3 to 7.8×10^3 kcal/m³, it is worthy of being recovered and reused to lower the carbon dioxide emissions in addition to reducing energy consumption.

Benefits of RTG Reuse

The fuel requirement for the pre-heating furnace is calculated based on the quantity needed to raise the furnace temperature to 320°C. Because FO, NG and RTG have different heat values, using the heat generated by burning 1 m³ of FO as the basis, 1.12 m³ of NG and 1.3 m³ of FG are needed to generate the same amount of heat. Hence ratios of fuel heat values are 1.0 for FO, 1.12 for NG and 1.3 for FG; these ratios are used in the following formula: volumetric flow rate of fuel = percentage of opening for control value \times maximum value volumetric flow rate \times ratio of fuel heat value. The temperature control of the hot fluid emitted from the pre-heating furnace is linked to the RTG flow rate control valve. When the NG flow rate is reduced causing the temperature of the emitted hot fluid to drop, the control valve automatically opens up to increase the RTG flow rate (with 0.3% of error) until the temperature of the exiting hot fluid resumes the pre-selected value as shown in Fig. 2.

Influence of Adding RTG on Flame Appearance

The fuel hydrogen content or C/H ratio significantly

influences the flame appearance (Ko and Lin, 2003; Ko et al., 2005); more hydrogen content leads to lower C/H ratio in the fuel so that both flame brightness and length are reduced (Fig. 3). The flame lengths are 47.5 cm/s for pure CH₄, 34 cm/s for 30/70 (%) of H₂/CH₄, and 31.5 cm/s for 50/50 (%) of H₂/CH₄ in the fuel. Similarly, adding RTG, which is rich in hydrogen, to the natural gas fuel causes reduced flame length and brightness; the observation is confirmed by laboratory studies using the methane gas fuel spike with hydrogen. The flame of burning pure natural gas has orange-yellowish color, its formation region covers the center to the end tip of the flame with a blue central extended from the burner tip (Fig. 4(a)). The orange-yellowish flame is caused by the formation, growth, and oxidation of the soot. Increasing the percentage of RTG in natural gas causes the orange-yellowish flame to be surrounded by a blue halo, and hence both the flame length and brightness appear to diminish. The combustion of pure RTG shows blue flame in the middle with only a slight orange color near the flame edge region (Fig. 4(b)).

In the RTG/NG/FO mixture burning system, the flame shows a bright orange and yellow color; the formation region starts from the middle of the flame to the outer edge. The flame is blue in the central region, and bright orange and yellow toward the outer edge (Fig. 4(c)). If NG in the RTG/NG/FO mixed fuel is completely replaced by RTG (mixture of FO and RTG only), the blue flame in the central region becomes relatively brighter, whereas the flame length and brightness obviously reduce as seen in Fig. 4(d).

Influence of RTG Addition on Adiabatic Flame Temperature and NO_x Formation

When the combustion is complete without any loss of heat, or changes in the kinetic or potential energy, the maximum

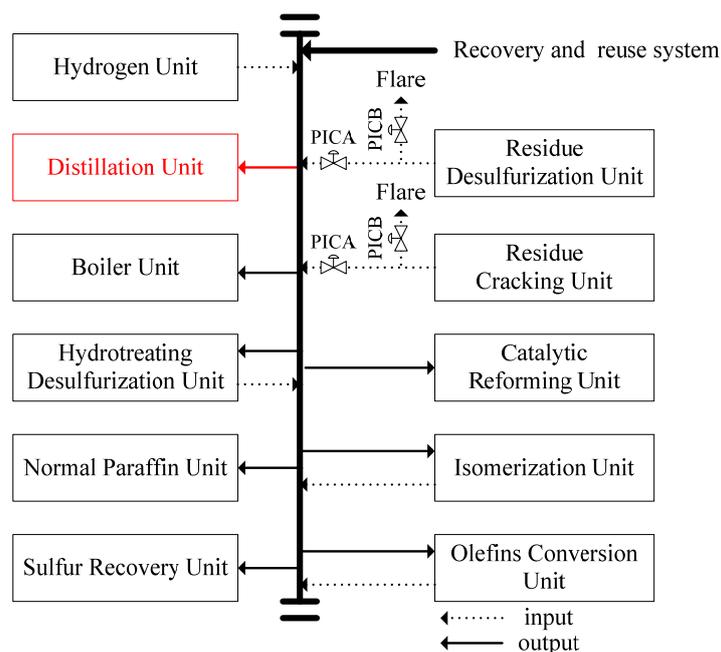


Fig. 1. Recovered waste gas management and fuel gas reuse system.

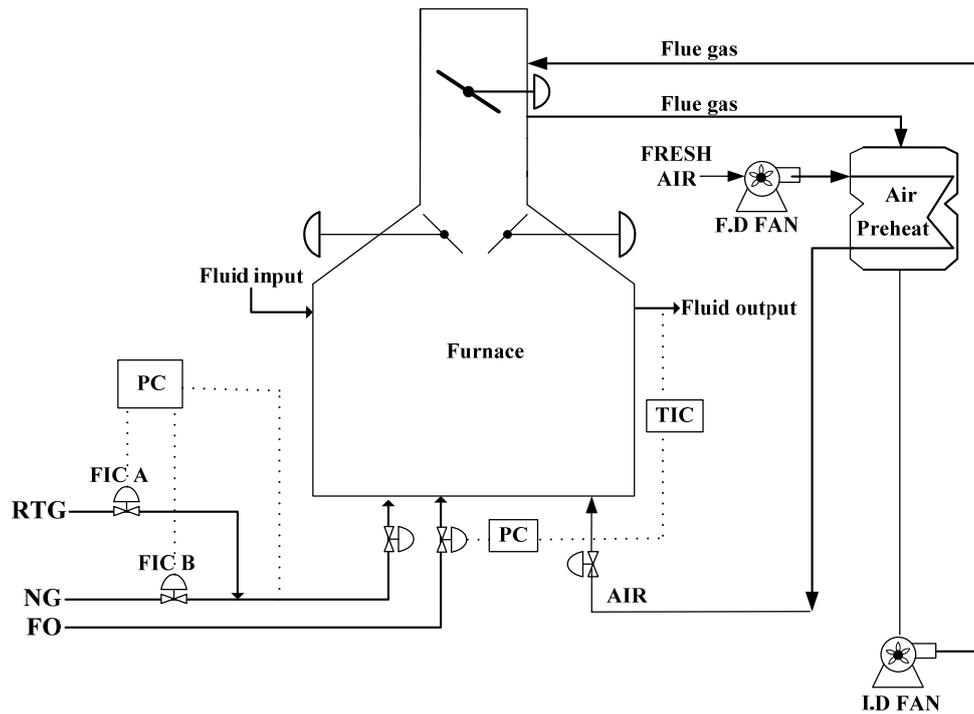


Fig. 2. Schematic diagram of the heating furnace system used for testing the reuse of recovered waste fuel gas.

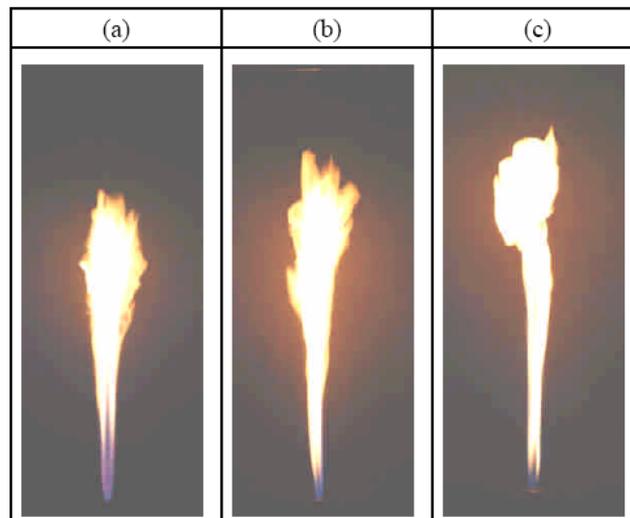


Fig. 3. Photographs of the flame appearance of a Co-axial double-ring jet spray burners for various fuel H_2/CH_4 ratio: (a) $H_2/CH_4 = 50/50\%$; (b) $H_2/CH_4 = 30/70\%$; (c) pure CH_4 .

temperature of the product is known as the adiabatic flame temperature (Turns, 2003). The adiabatic flame temperature of a steady-flow combustion process for various inlet RTG/NG and RTG/NG/FO ratios can be calculated based on thermochemistry and chemical equilibrium of the products. The calculation is based on the assumption that the combustion process is under a constant pressure so that the dissociation of the combustion products can be neglected. When the hydrogen content in RTG is 30% mole, the adiabatic flame temperature reaches about 1850°C , whereas the fuel with H_2 content of 80 mole% leads to 1950°C of adiabatic flame temperature.

Although higher RTG addition that causes lower fuel CH concentration may bring about lower prompt NO_x formation, the increasing ratio of hydrogen in the mixed fuel may raise the adiabatic flame temperature to augment the formation of thermal NO_x . Because the thermal NO_x formation is the dominant formation mechanism in regions of such high temperatures (Tsai *et al.*, 2011; Abu-Allaban and Abu-Qudais, 2011), higher RTG addition is expected to result in an increase of the total NO_x formation. Table 1 shows that in the RTG/NG mixtures burning system, about 22.9 ppmv of NO_x is formed by burning pure NG. The NO_x formation is raised to 39.8 ppmv when the inlet RTG/NG ratio is

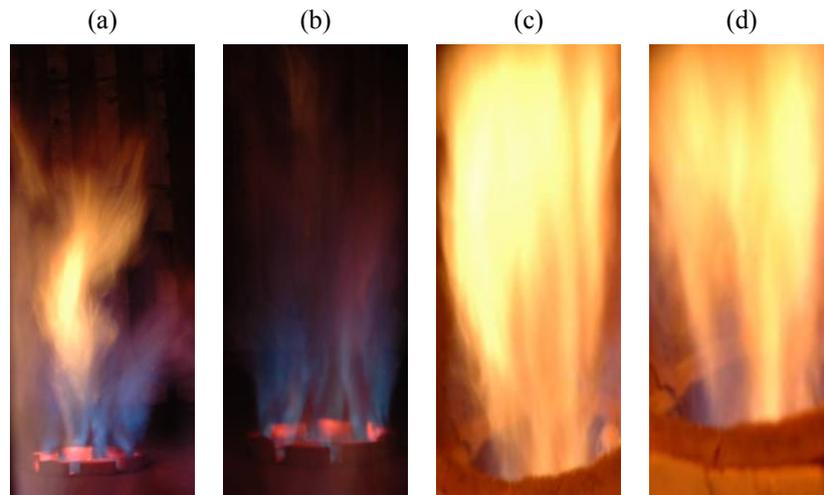


Fig. 4. Photographs of the flame appearance of a multi-port burner for various fuel RTG/NG ratio: (a) pure NG; (b) Pure RTG; (c) (FO + NG); (d) (FO + RTG).

Table 1. The furnace for adjust RTG/NG/FO volumetric flow rate ratio.

Parameter	Inlet different fuel volumetric flow rate ratio (%)					
	RTG/NG system burning			RTG/NG/FO system burning		
	Pure NG	RTG /NG = 50:50	Pure RTG	NG/FO = 50:50	RTG/NG/FO = 25:25:50	RTG/FO = 50:50
NO _x (ppmv)	22.9	39.8	59.6	65.9	69.3	74.0
Residual O ₂ conc. (Vol,%)	2.8	3.4	4.3	2.6	3.3	4.4
Preheat air temp. (°C)	232	229	221	156	154	153

50/50. If NG is completely replaced by the recovered RTG, the NO_x formation increases to 59.6 ppmv. In addition, in the RTG/NG/FO burning system, the inlet RTG/NG/FO ratio of 0/50/50 (i.e. NG/FO fuel) produces on the average 65.9 ppmv of NO_x, whereas the inlet RTG/NG/FO ratio of 25/25/50 raises the NO_x formation to 69.3 ppmv. The inlet RTG/NG/FO ratio of 50/0/50 (i.e. RTG/FO fuel) further causes the NO_x formation to rise to 74.0 ppmv.

Influence of RTG Addition on Residual O₂ Concentration and Sensible Heat loss

The air required (A_o) for a complete combustion is calculated using the following equation:

$$A_o = \frac{1}{0.21} \left(\begin{array}{l} 0.5H_2 + 2CH_4 + 3C_2H_4 + 3.5C_2H_6 \\ + 5C_3H_8 + 6.5C_4H_{10} \end{array} \right) \quad (1)$$

Based on Eq. (1), the theoretical air requirements for a complete combustion are 10.4 m³ for NG and 6.5 m³ for RTG.

In the system burning RTG/NG, the residual O₂ concentration is 2.8 Vol.% for pure NG; it increases to 3.4 Vol.%, for 50/50 inlet RTG/NG ratio and further to 4.3 Vol.% for pure RTG (Table 1). In the system burning RTG/NG/FO, the residual O₂ concentration for burning the original fuel mixture (NG/FO) is 2.6 Vol.%. When the inlet RTG/NG/FO ratio is 25/25/50 (50% NG replaced by RTG), the residual O₂ concentration is raised to 3.3 Vol.%.

In the system burning the RTG/FO fuel, the residual O₂ concentration further increases to 4.4 Vol.%. Higher O₂ concentration implies that more air enters the furnace so that the temperature in the furnace reactive region is reduced (Hill and Smoot, 2004; Naha and Aggarwal, 2004; Kuprianov, 2005).

Hydrogen has high energy and low flame radiation (Hill and Smoot, 2004); increasing hydrogen concentration in the fuel causes the flame width to increase but the flame length to decrease. Hence the fuel stream that contains more hydrogen has a shorter retention time in the furnace convective region (Choudhuri *et al.*, 2003). Increasing the amount of RTG in the mixed fuel causes higher hydrogen content, broader flame width, less flame length, reducing the overall time for the hot gas stream to stay in the furnace convective zone so that the heat absorbed in the furnace is reduced to lower the local heat transfer rate in the furnace radiation zone.

Table 1 shows that in the system burning RTG/NG, the preheated air temperature for burning pure NG reaches 232°C; it drops to 229°C for burning 50/50 RTG/NG, and further to 221°C for burning pure RTG. Eq. (2) can be used to calculate the heat loss and the required preheating temperature:

$$\Delta H = mC_p\Delta T \quad (2)$$

In this equation, ΔH is air sensible heat (kcal/hr); m is the air flow rate (m³/hr); C_p is the air heat capacity (kcal/m³·°C);

and ΔT is the temperature difference ($^{\circ}\text{C}$). The average sensible heat loss in the RTG/NG system is 7.2×10^4 kcal/hr. In the system burning NG/FO, the preheated air temperature is 156°C . When the inlet RTG/NG/FO ratio is 25/25/50, the preheated air temperature is drops to 154°C , and for the RTG/FO system (i.e. NG is completely replaced by RTG), the preheated air temperature is further drops to 153°C with an average sensible heat loss of 2.5×10^4 kcal/hr.

Influence of RTG Addition on CO_2 Production

The calculated quantities of carbon dioxide produced for complete combustion are 1140 kg/m^3 for RTG, 2160 kg/m^3 for NG, and 2790 kg/kg for FO. If NG is completely replaced by RTG, $4.0 \times 10^3 \text{ kg/m}^3\text{h}$ or 53.4% of CO_2 can be reduced. In the RTG/NG/FO system, the complete replacement of NG contained in the original NG/FO fuel by RTG (i.e. RTG/FO) reduces $2.6 \times 10^3 \text{ kg/m}^3\text{h}$ or 30.0% of CO_2 . These results conform to the report in literature that adding 60% of hydrogen to natural gas reduces about of 33% CO_2 emissions (Guo et al., 2005).

Analysis of Advantages

This study demonstrates outstanding improvements on the reduction of fuel costs and environmental pollutant emissions by replacing NG fuel or the NG of the NG/FO fuel with RTG (i.e. the RTG/FO fuel). Replacing pure NG with RTG saves 24.6% fuel costs, whereas replacing NG in the NG/FO mixture system saves 19.5% of fuel costs. In addition, replacing all NG with RTG in the system burning NG can reduce 53.0% of emissions annually. Replacing the NG in the NG/FO mixture fuel achieves 30.0% reduction of CO_2 emissions.

Therefore, if properly recovered and managed to maintain an adequate pressure, the energy contained in the tail gas emitted from petroleum refinery process can be reused as a reliable alternative energy source. In this paper, using RTG to replace NG to fuel the furnace is shown to increase NO_x formation and average sensible heat loss. These undesirable characteristics can be remedied by decreasing residual O_2 concentration in the flue gas through controlling the flow rate of fresh air into the combustion chamber to alleviate NO_x emission and sensible heat loss. The management and control methods demonstrated in this study is expected to assist industries in achieving energy saving and reducing greenhouse gas emission.

CONCLUSIONS

The waste tail gas emitted from the various petroleum refinery process, primarily from the residue desulfurization unit and the residue cracking unit, is recovered; its pressure is properly controlled and managed to form a stable sources of alternative fuel. In this paper, the direct use of the recovered waste tail gas to replace natural gas for fueling a full-scale furnace is presented. The on-site experimental results show that replacing natural gas (NG) by the tail gas (RTG) recovered from some petrochemical processes saves 24.6% of fuel costs and reduces 53.0% of CO_2 emissions. If the natural gas (NG) in a mixed fuel containing both

natural gas and fuel oil (NG/FO) is completely replaced by RTG, the resulting RTG/FO or RTG/NG/FO fuel mixtures saves 19.5% of fuel costs and reduces 30.0% of pollution emissions.

On the other hand, the RTG gas has high hydrogen content of 60 mole% on average (30–80 mole%); it requires relatively lower theoretical air requirement to burn than NG. When NG is completely replaced by RTG in either RTG/NG or RTG/NG/FO mixture, the resulting residual O_2 concentration in flue gases is raised. Additionally, the increasing amount of RTG in the mixed fuel causes higher hydrogen content, broader flame width and shorter flame length so that the adiabatic flame temperature is raised. Because the available oxygen in the burning zone and flame temperature are the major two factors to affect the NO_x formation, the use of RTG causes higher NO_x formation in either RTG/NG or RTG/NG/FO burning system. However, this characteristic of higher NO_x formation and sensible heat loss when NG is replaced by RTG can be alleviated by decreasing residual O_2 concentration in the flue gas through controlling the flow rate of fresh air into the combustion chamber. Thus, from the viewpoint of the overall economics and sustainable energy policy, if properly implemented and managed, the recovered waste tail gas is expected to assist industrial nations in raising the overall energy efficiency and reducing the net energy consumption.

REFERENCES

- Abu-Allaban, M. and Abu-Qudais, H. (2011). Impact Assessment of Ambient Air Quality by Cement Industry: A Case Study in Jordan. *Aerosol Air Qual. Res.* 11: 802–810.
- Bari, M. A., Baumbach, G., Kuch, B. and Scheffknecht, G. (2011). Air Pollution in Residential Areas from Wood-fired Heating. *Aerosol Air Qual. Res.* 11: 749–757.
- Barroso, J., Barreras, F. and Ballester, J. (2004). Behavior of a High-capacity Steam Boiler Using Heavy Fuel Oil Part I. High-temperature Corrosion. *Fuel Process. Technol.* 86: 89–105.
- Bhaskar, B.V. and Mehta, V.M. (2010). Atmospheric Particulate Pollutants and Their Relationship with Meteorology in Ahmedabad. *Aerosol Air Qual. Res.* 10: 301–315.
- Bojic, M. and Mourdoukoutas, P. (2000). Energy Saving Does Not Yield CO_2 Emission Reductions: The Case of Waste Fuel Use in a Steel Mill. *Appl. Therm. Eng.* 20: 963–975.
- Caputo, A.C., Scacchia, F. and Pelagagge, P.M. (2003). Disposal of by-products in Olive Oil Industry: Waste-to-energy Solutions. *Appl. Therm. Eng.* 23: 197–214.
- Chen, W.S., Shen, Y.H., Hsieh, T.Y., Lin, C.W., Wang, L.C. and Chang-Chien, G.P. (2011). Fate and Distribution of Oolychlorinated Dibenzo-p-dioxins and Dibenzofurans in a Woodchip-fuelled Boiler. *Aerosol Air Qual. Res.* 11: 282–289.
- Choi, I.H. and Jo, W.K. (2011). Application of Stack Emissions Data from Tele-monitoring Systems for Characterization of Industrial Emissions of Air Pollutants.

- Aerosol Air Qual. Res.* 11: 412–418.
- Choudhuri, A.R. and Gollahalli, S.R. (2003). Characteristics of Hydrogen- hydrocarbon Composite Fuel Turbulent Jet Flames. *Int. J. Hydrogen Energy* 28: 445–454.
- Dincer, I. and Rosen, M.A. (1999). Energy, Environment and Sustainable Development. *Appl. Energy* 64: 427–440.
- Guo, H., Smallwood, G.J., Liu, F., Ju, Y. and Gülder, Ö.L. (2005). The Effect of Hydrogen Addition on Flammability Limit and NO_x Emission in Ultra-lean Counterflow CH₄/Air Premixed Flames. *Proc. Combust. Inst.* 30: 303–311.
- Hennicke, P. and Fishedick, M. (2006). Towards Sustainable Energy Systems: The Related Role of Hydrogen. *Energy Policy* 34: 1260–1270.
- Hill, S.C. and Smoot, L.D. (2004). Modeling of Nitrogen Oxides Formation and Destruction in Combustion Systems. *Prog. Energy Combust. Sci.* 26: 417–458.
- Holmgren, K. and Henning, D. (2004). Comparison between Material and Energy Recovery of Municipal Waste from an Energy Perspective a Study of Two Swedish Municipalities. *Resour. Conserv. Recy.* 43: 51–73.
- Hsieh, S.C. and Jou, C.J.G. (2007). Reduction of Greenhouse Gas Emission on a Medium-pressure Boiler through Hydrogen-rich Fuel Control. *Appl. Therm. Eng.* 27: 2924–2928.
- Hu, J.L. and Kao, C.H. (2007). Efficient Energy-saving Targets for APEC Economies. *Energy Policy* 35: 373–382.
- Jou, C.J.G., Lee, C.L., Tsai, C.H. and Wang, H.P. (2008a). Reduction of Energy Cost and CO₂ Emission for the Boilers in a Full-scale Refinery Plant by Adding Waste Hydrogen-rich Fuel Gas. *Energy Fuels* 22: 564–569.
- Jou, C.J.G., Lee, C.L., Tsai, C.H., Wang, H.P. and Lin, M.L. (2008b). Enhancing the Performance of a High-pressure Cogeneration Boiler with Waste Hydrogen-rich Fuel. *Int. J. Hydrogen Energy* 33: 5806–5810.
- Ko, Y.C., Hou, S.S. and Lin, T.H. (2005). Laminar Diffusion Flames in a Multi-port Burner. *Combust. Sci. Technol.* 177: 1463–1484.
- Ko, Y.C. and Lin, T.H. (2003). Emissions and Efficiency of a Domestic Gas Stove Burning Natural Gases with Various Compositions. *Energy Convers. Manage.* 44: 3001–3014.
- Kuprianov, V.I. (2005). Applications of a Cost-based Method of Excess Air Optimization for the Improvement of Thermal Efficiency and Environmental Performance of Steam Boilers. *Renewable Sustainable Energy Rev.* 9: 474–498.
- Lee, C.L., Jou, C.J.G., Tai, H.S., Wang, C.H., Hsieh, S.C. and Wang, H.P. (2006). Reduction of Nitrogen Oxides Emissions of a Medium-pressure Boiler through Fuel Control. *Aerosol Air Qual. Res.* 6: 123–133.
- Lee, C.L., Jou, C.J.G., Tsai, C.H. and Wang, H.P. (2007). Improvement of a Medium-pressure-boiler Performance through Adjustments on the Hydrogen-rich Fuel for Refinery Plant. *Fuel* 86: 625–631.
- Lund, H. (2007). Renewable Energy Strategies for Sustainable Development. *Energy* 32: 912–919.
- Lunghi, P. and Burzacca, R. (2004). Energy Recovery from Industrial Waste of a Confectionery Plant by Means of BIGFC Plant. *Energy* 29: 2601–2617.
- Marchettini, N., Ridolfi, R. and Rustici M. (2007). An Environmental Analysis for Comparing Waste Management Options and Strategies. *Waste Manage.* 27: 562–571.
- Naha, S. and Aggarwal, S.K. (2004). Fuel Effect on NO_x Emission in Partially Premixed Flames. *Combust. Flame* 139:90–105.
- Ning, Z. and Sioutas, C. (2010). Atmospheric Processes Influencing Aerosols Generated by Combustion and the Inference of their Impact on Public Exposure: A Review. *Aerosol Air Qual. Res.* 10: 43–58.
- Ozalp, N. and Hyman, B. (2006). Calibrated Models of on-site Power and Steam Production in US Manufacturing Industries. *Appl. Therm. Eng.* 26:530–539.
- Ptasinski, K.J., Koymans, M.N. and Verspagen, H.H.G. (2006). Performance of the Dutch Energy Sector Based on Energy, Exergy and Extended Exergy Accounting. *Energy* 31: 3135–3144.
- Ruttanachot, C., Tirawanichakul, Y. and Tekasakul, P. (2011). Application of Electrostatic Precipitator in Collection of Smoke Aerosol Particles from Wood Combustion. *Aerosol Air Qual. Res.* 11: 90–98.
- Thollander, P., Danestig, M. and Rohdin, P. (2007). Energy Policies for Increased Industrial Energy Efficiency: Evaluation of a Local Energy Programme for Manufacturing SMEs. *Energy Policy* 35: 5774–5783.
- Tsai, J.H., Huang, K.L., Chiu, C.H., Lin, C.C., Kuo, W.C., Lin, W.Y., Chaung, H.C., Yang, T.H. and Chen, S.J. (2011). Particle-bound PAHs and Particle-extract-induced Cytotoxicity of Emission from a Diesel-generator Fuelled with Soy-biodiesel. *Aerosol Air Qual. Res.* 11: 822–836.
- Turns, S.R. (2003). *An Introduction to Combustion: Concepts and Applications*, Second Edition, McGraw Hill, p. 32–35.
- Vega, E., Eidels, S., Ruiz, H., López-Veneroni, D., Sosa, G., Gonzalez, E., Gasca, J., Mora, V., Reyes, E., Sánchez-Reyna, G., Villaseñor, R., Chow, J.C., Watson, J.G. and Edgerton, S.A. (2010). Particulate Air Pollution in Mexico City: A Detailed View. *Aerosol Air Qual. Res.* 10: 193–211.
- Xue, H. and Aggarwal, S.K. (2003). NO Emission in n-heptane/Air Premixed Flames. *Combust. Flame* 132: 723–741.
- Worrell, E., Price, L. and Martin, N. (2001). Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Iron and Steel Sector. *Energy* 26: 513–536.
- Wu, T.S., Hsieh, L.T., Lin, S.L., Chang, Y.C., Chen, C.B. and Hung, C.H. (2010). Emissions from Using Viscous Agent-treated Fishing Boat Fuel Oil: Tests with a Heavy-duty Diesel Engine (HDDE) Dynamometer. *Aerosol Air Qual. Res.* 10: 76–85.

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