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# Study for the gas interchangeability of natural gas utilization equipment regarding the variation of heating value

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## 1. Introduction

A system improvement to change the current fixed standard of domestic natural gas heating value system of 10,400kcal/N㎥ to a heating value range system of 10,200±4%(9,800~10,600)kcal/N㎥ was propelled starting in 2012. According to the improvement measures the first phase is 2012~2014 and a heating value range of 10,000~10,600 kcal/Nm³ is supplied and if the performance is not seen as problematic in that term, phase two which starts in 2015, will set the range to 9,800~10,600kcal/Nm³. The significance of this system is to reduce the costs through heating value management and bring stability to the supply of domestic natural gas by responding to the downward trend in the international natural gas heating value.

For this purpose a household/business'sensitive device was selected. For the industry device, 1,199 companies went through questionnaire surveys and through a sensitive process analysis 46 companies were selected. A series of studies were conducted to demonstrate the selected sensitive device and the process' heating value private map.

## 2. Theoretical review

Combustion material properties affected by the heating value of fuel is as follows and will be investigated.

### 2.1 Stoichiometric air fuel ratio

The air quantity necessary for the combustion of hydrocarbon-based fuel( $C_xH_y$ ) is found through equation (1)'s stoichiometric reaction equation and the relationship equation (2) of the fuel-air quantity required for this reaction.

$$C_x H_y + a(O_2 + 3.76 N_2) \rightarrow x CO_2 + (y/2) H_2 O + 3.76 a N_2 \tag{1}$$

$$(A/F)_{stoic.} = \left(\frac{m_{air}}{m_{fuel}}\right)_{stoic.} = \frac{4.76a}{1} \frac{MW_{air}}{MW_{fuel}} \tag{2}$$

Here, $a = x + y/4$

Furthermore the gas mixture unit per mole or unit per mass is each found in equation(3) and equation (4).

$$\overline{H^\circ} = \sum_{j=1}^{N} x_j \cdot \overline{H_j^\circ} \tag{3}$$

$$\widehat{H^\circ} = \frac{\overline{H^\circ}}{M} \tag{4}$$

Here, $\overline{H^\circ}$ : ideal mole fraction heating value of gas mixture

$\overline{H_j^\circ}$ : ideal mole fraction heating value of j component

$x_j$ : mole fraction of j component

$M$ : molecular weight of gas mixture

$\widehat{H^\circ}$ : ideal heating value of gas mixture per unit mass

Therefore in cases such as LNG where the fuel does not have nitrogen components, a relationship as the picture below is established between the heating value and stoichiometric ratio. It means that if the heating value changes, each heat system's optimized air/fuel ratio will be changed also, hence it is very important to decide the heating value range that can be accepted in every heat system.

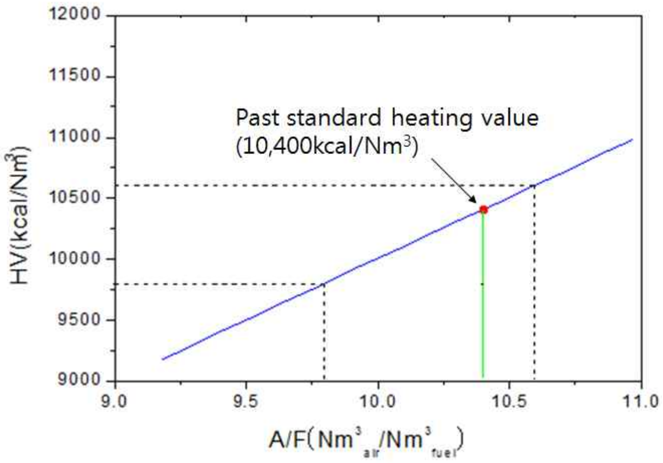



Fig. 1 Relationship between the heating value and stoichiometric ratio

2.2 Power

The Wobbe Index of gas mixture is the most useful index in determining the compatibility of the gas fuel and in case of the same supply condition(same supply pressure and burner nozzle), it is an index that holds a proportional relationship in power supplied to the device. Therefore, according to the Bernoulli equation, if the supply pressure is the same, the gas flowrate that is supplied to the device is inversely proportional to the square root of the density, so this Wobbe Index is defined in the form of dividing by the square root of the density of the heating value by the fuel.

The Wobbe Index of the mixture which is the ideal gas, is found with equation (5) and the mixer's relative density is calculated with equation (6).

$$WI^{\circ} = \frac{\widetilde{H^{\circ}}}{\sqrt{d^{\circ}}} \quad (5)$$

$$d^{\circ} = \sum_{j=1}^{N} x_j \times \frac{M_j}{M_{air}} \quad (6)$$

여기서, $WI^{\circ}$ : Wobbe Index of ideal gas

$d^{\circ}$ : relative density of ideal gas

$M_j$ : moleqular weight of j component

$M_{air}$ : moleqular weight of dry air

2.3 Adiabatic flame temperature

Figure 2 charts the adiabatic chemical equilibrium temperature based on the equivalence ratio of natural gas based on production location. The ref. gas represents 10,500kcal/N㎥ heating value, the BOG1 represents pure methane, and BOG2 represents a methane gas that has 2% mixture of nitrogen. With a condition of equivalence ratio of 1.0, the order of chemical equilibrium temperature is as follows: Australia > Ref. gas > Yemen > BOG1 > Sakhalin > Russia > Egypt > BOG2. If the quantitative difference is observed with the Ref. gas as a standard, the BOG2 reveals 26.2 K difference while Australia shows 0.1 K with barely any difference.

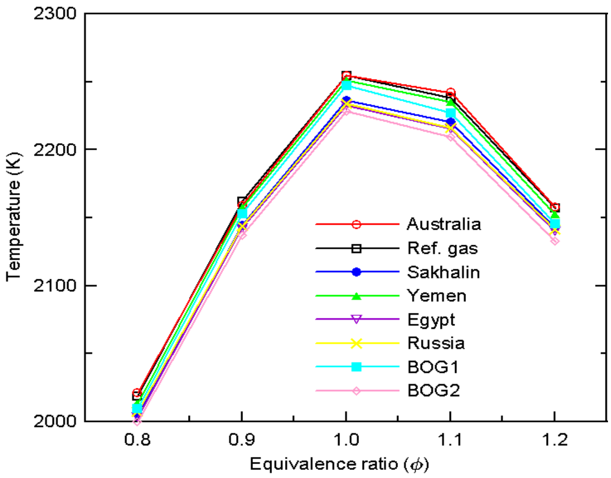



Fig. 2 Adiabatic flame temperature according to equivalence ratio of natural gas based on production location

2.4 Burning velocity

The burning velocity represents the movement speed of the flame front in a stationary mixture, but when seeing the flame front as a standard, it represents the speed of the perpendicular inflow towards the unburned gas and it is expressed as laminar and turbulent flame speed. This burning velocity is influenced by fuel component, equivalent ratio, gas supply temperature, combustion temperature, pressure and etc. and they are important factors that determine the flame stability, load, and etc. when designing the combustor.

As above, the heating value gives various influence to combustion factors and in actual heat systems these combustion factors influence occur in combinations, hence the influence on the heat system based on the change of heat value is difficult to predict so it is most effective to predict the results through actual demonstration tests and process simulation with an actual combustor.

## 3. Experimental apparatuses and methods

The experiment devices were sectored to demonstrate the effect of heating value by a use group. The sectors were divided into household, business, industry, transportation and stationart engine. In the case of household use, the premixed burner which is sensitive to flame safety was included and in the case of the industry use, through a questionnaire survey analysis of 1,199 companies 50 companies were ultimately selected and a sensitivity process was selected on that basis. As a result it was compressed into steel/glass field and fired drying field.

Table 1 organizes the information about the experiment gas used in the experiment. The utilized natural gas heat value range is 9,332~10,835 kcal/$Nm^3$, BOG1 is pure methane, and BOG2 represents methane gas mixture with 2% of nitrogen.

Table 1 Thermodynamic properties of 8 natural gases

| | Australia | Ref. gas | Sakhalin | Yemen | Egypt | Russia | BOG | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1 | 2 |
| Higher heating value (kcal/$Nm^3$) | 10835 | 10550 | 10295 | 10096 | 9781 | 10024 | 9523 | 9332 |
| Wobbe index (kcal/$Nm^3$) | 13492 | 13325 | 13186 | 13095 | 12927 | 12855 | 12784 | 12436 |
| $[A/F]_{stoi.}$ ($m^3/m^3$) | 10.8242 | 10.5415 | 10.2878 | 10.0891 | 9.7761 | 10.0046 | 9.5200 | 9.3296 |

# 4. Results and discussions

## 4.1 Residential

The figure 3 charts the thermal efficiency when gas is exchanged by maintaining the supply pressure to 200mmAq in a household gas device. Experiment results had 6 types of gas devices as subjects and experiment results of each of the 6 type of gases were charted. Based on this picture it can be observed that the differences were so minute that it is almost difficult to determine the thermal efficiency difference. Excluding BOG1 and 2, the relative efficiency difference was less than 1.5% so there was not much difference in thermal efficiency even with a gas type change.

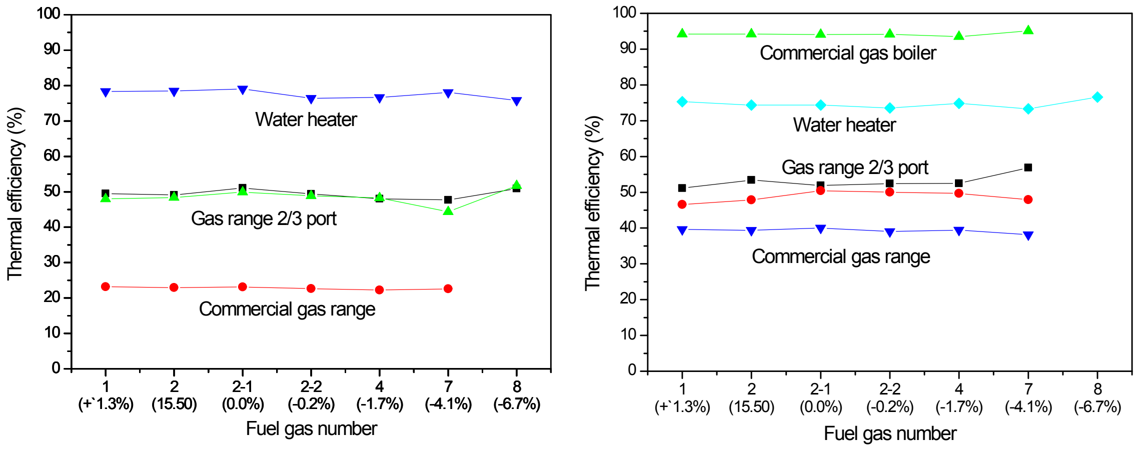
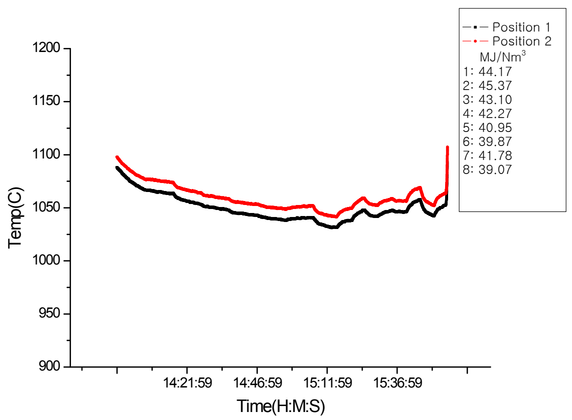



Fig. 3 Thermal efficiency of various residential device according to natural gas based on production location

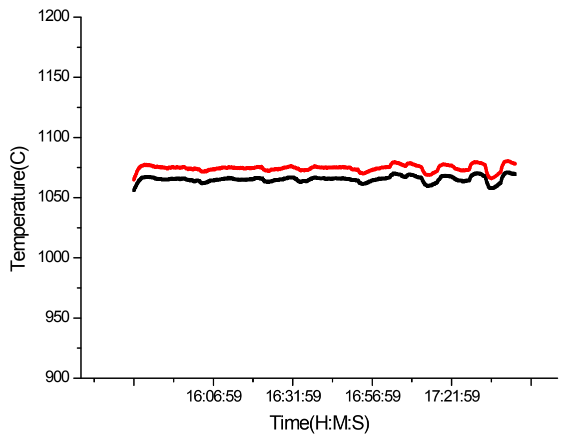
## 4.2 Industrial

The figure 4 (a) charts the furnace temperature changes caused by heating value change in the fired furnace of the steel industry. The figure charts the furnace temperature change on random gas injection. Position 1 in the figure is the front portion of the furnace and position 2 is the temperature measurement in the back portion of the furnace. The system reached steady status since the injection from number 6 (Russia) on the left and hence it was seen that it was in a parallel state and then gas was randomly varied to observe the change in furnace temperature. The long sections in the picture were set to 10 minutes and the short sections were set to 5 minutes. In the furnace heat of around 1,050℃, a 16% heat value change (difference between number 1 gas and number 8 gas) displayed a maximum difference of around 20℃.

The figure 4 (b) reveals the temperature traceability acquired through temperature control and air-fuel ratio control when the furnace temperature was set as 1,070℃. As the gas composition is changed the temperature changes quickly and then after 5 minutes it almost reaches the set temperature. With a 16% heating value change, the maximum temperature error was around 3℃ within 5 minutes. When seen with control tracking, it is 97% within 5 minutes based on 16% heat value change. When more time is given for around 10 minutes there is a 1 degree temperature error, so control traceability of around 99% is observable.




(a) Uncontrolled furnace temperature




(b) controlled furnace temperature

Fig. 4 Temperature profile in the furnace according to natural gas based on production location

Figure 5 shows the degree of oxidation/reduction atmosphere ($CO_2$/CO) based on heating value change in a fired reducing furnace of the steel industry in various operating conditions. As observable on the picture, number 1~4 gases change in an average of 5% but numbers 5~8 change in an average of 15% and a maximum of 20%. This is a result that reveals that as the heating value decreases the oxidation atmosphere increases, which may be a level that can influence manufactured products.

The figure 6 is the result of oxidation/reduction atmosphere level in the metal industry's DX annealing furnace based on heating value change. In the case of $CO_2$/CO, gas number 1 to 6 has a fluctuation range within 5% and number 7 and 8 have a rather large fluctuation range of 15%. This phenomenon occurs because as the heat value reduces, the theoretical air amount also reduces and results in changing into an oxidation atmosphere. This state may also affect the performance of the manufacture product. The figure (b) reveals the $H_2$ density based on heating value change and overall, the changing trends are similar as $CO_2$/CO. The figure (c) shows the oxygen density based on heating value change and numbers 1~6 shows 30% of fluctuation range while 7 and 8 shows up to 80%, showing much difference compared to gas number 1. The reason for the larger $O_2$ fluctuation compared to the HC is seen as a result because of the unburnt combustion condition air/fuel does not mix well on the burner nozzle section. This also can be seen as a reduction burner's characteristic. Therefore when these results are observed, the atmosphere control is very difficult and important when the DX gas generating device is used within the furnace and to efficiently control the $O_2$, a simple controller is not sufficient so a controller with a purge concept is necessary. This is because in the change of $CO_2$/CO and $O_2$ which reveals the atmosphere level, the air-fuel ratio that affects the $CO_2$/CO and $O_2$ are all slightly different.

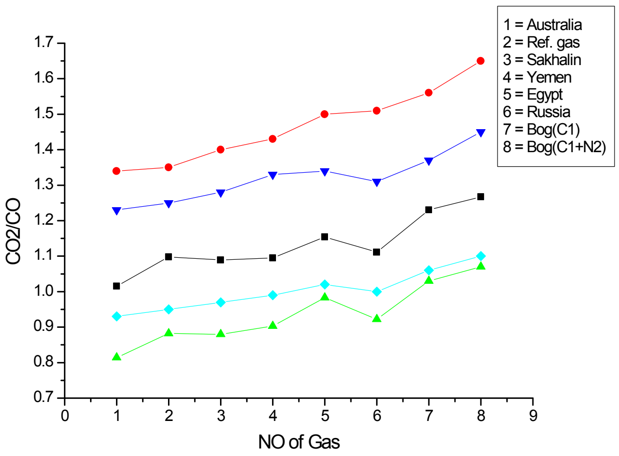
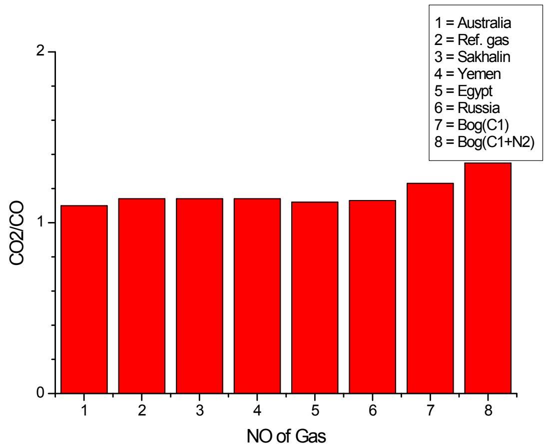
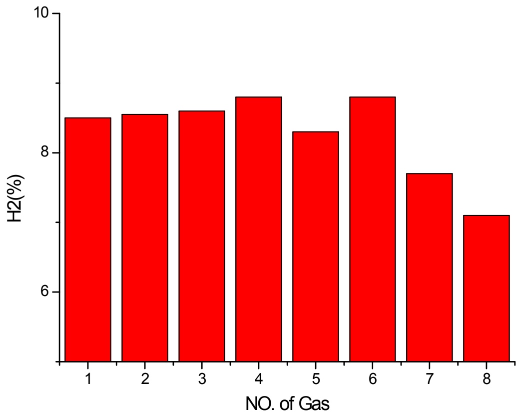



Fig. 5 Ratio profile of $CO_2$/CO in a fired reducing furnace according to natural gas based on production location

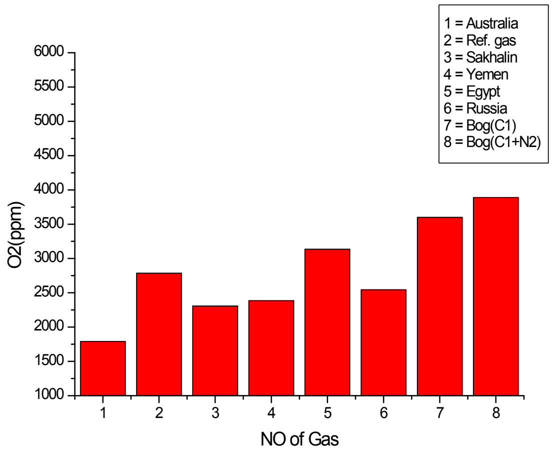



(a) Tendency of $CO_2$/CO

The figure 7 is a case where enriched gas was injected in the carburizing furnace and the CP was measured to analyze the influence of the 8 type of gases. When the heating value decreases the range of fluctuation to 16%, it is different according to the operation possible air-fuel ratio but in a RX generating device around 2-4% of CO reduction and around 1-3% level of $H_2$ reduction causes a decreased carburizing atmosphere. Conclusively the CP which was 0.7 with gas number 1 decreased to 0.4 with gas number 8 and this is around 0.3% density difference when seen in terms of surface carbon density. Therefore as a characteristic of the carburizing operation it is a very large value and when observed based on gases from gas number 1 to gas number 4, the CO is less than 2% and the $H_2$ has a fluctuation rage of 0.5% so it is a relatively small change, but when seen with CP there is a 0.1% carbon density difference. In the actual carburizing furnace a carbon density above 0.1% difference becomes a problem so when injecting the gases of number 5~8, CP control is very necessary.




(b) Tendency of $H_2$




(c) Tendency of $O_2$

Fig. 6 Tendency of atmosphere gas in DX reduction furnace according to natural gas based on production location

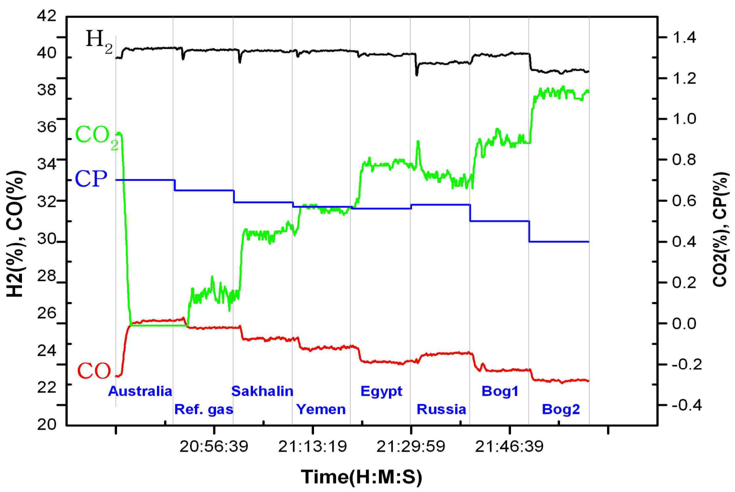



Fig. 7 Profile of oxidation/reduction gas in carburizing furnace according to natural gas based on production location

The photo 1 shows the cutted steel surface in accordance to oxygen cut torch transmission speed based on heat value change. In the cutting speed less than 300mm/min, all experiment gases obtained a good cut surface and when the speed was increased to 350 and 400 mm/min all gases produced a drag. Hence in the process of metal cutting with oxygen cut torch, the influence of heating value on manufactured product was confirmed to be minuscule.

The photo 2 charts the flame form's changes of the glass cutting flame based on gas types during glass and bulb processing process. The combustion condition of each gas was based on ref. gas standard and this experiment was processed assuming that the gas types were replaced in the condition of equivalence ratio of 0.77 and fuel flow rate of 0.8 l/min. As it can be observed on the picture, the influence of heating value on the length of glass cutting flame was very insignificant.

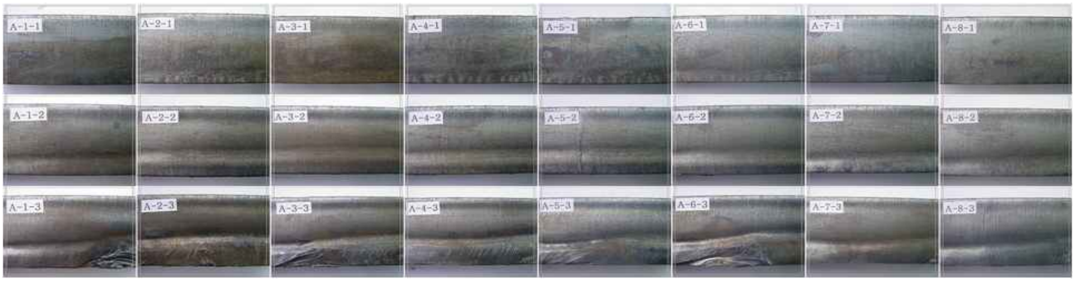



Photo 1 Condtion of cutted stell surface by oxigen torch fuel by natural gas based on production location

The figure 9 quantifies the duplicate heat flux based on gas types and it is an average value out of 20 data points which was made in a sufficient 5 minutes after the normal status. When the change based on heating value is observed, duplicate heat flux showed a reduction in the case of low heating value gas but the difference was very small and a clear tendency of decrease did not appear.

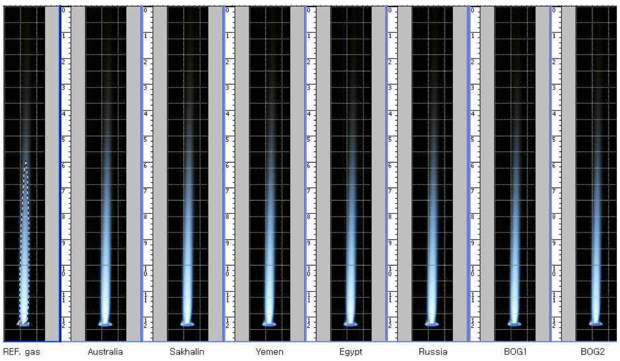



Photo 2 Flame shapes and lengths of 8 natural gases for cutting flame

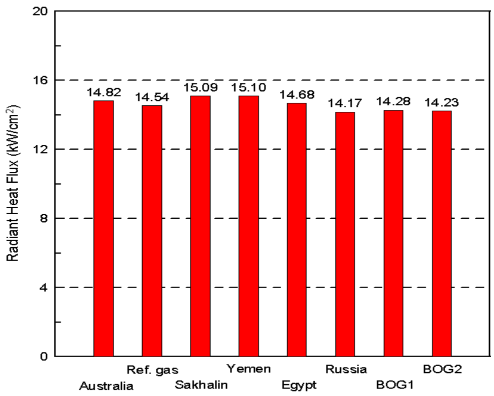



Fig. 8 Heat flux of natural gas flame based on production location

The photo 3 is a picture of flame where only the types of 8 gases are changed in the process of the radiation mode combustion condition which is similar to the direct fired drying process in the paper industry. The supply pressure of all gases were steadily maintained at 200 mmAq and all other equipment and artificial operating conditions were not altered. In the aspect of flame safety such as spark, backfire, and intensity of radiation based on gas heat value change, the differences were miniscule and almost impossible to identify with the naked eye.

The figgure 9 shows the temperature in each positions for the fired drier based on gas type. The temperature change tendency based on gas type change matches up to 10mm which is close to the burner surface. When the heating value decreased, in the same order the temperature became lower. When the temperature difference based on the different type of gas is compared with the surface temperature, with the ref. gas as a standard, Australia appear to be 8℃ higher, BOG1 appeared to be 15℃ lower, and BOG2 appeared to be 20℃ lower.

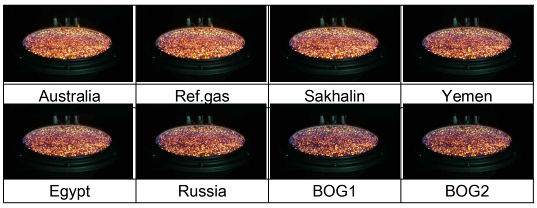



Photo 3 Radiation flame in metal fiber burner according to natural gas based on production location

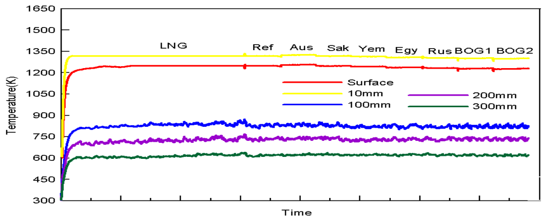



Fig. 9 Temperature profile of each position in direct fired drying burner according to natural gas based on production location

Therefore the temperature distribution in the vicinity of the burner is directly affected by supplied heating value based on the type of gas, and when the supplied heat value is smaller it can be said that temperature in the position became smaller. Meanwhile, in the actual paper drying height of 200mm the maximum temperature difference is 2℃ and it can be observed that there are barely any difference with any type of gas. It is believed that this is caused because when above the 100mm position, the temperature received more influence from the furnace atmosphere temperature than the burner's surface temperature so it is insensitive to the direct temperature change from the change of gas type.

## 5. Conclusions

A result as follows was achieved through the demonstration experiment in this study to observe how the natural gas heating value of 9,300~10,800 kcal/Nm$^3$ influences the performance factor of the gas utilizing devices in various industries.

1) In the case of household gas devices, most performance factors did not show a problem including the heat efficiency based on heating value change.

2) In the case of industry, in glass processing, direct fired drier and metal cut processing, at the process where the flame makes a direct influence, the heating value did not make a large influence and it is considered that this is due to the fuel composed of the main component of methane with hydrocarbon affiliation where the change of heat value has small influence on the combustion characteristic.

3) Meanwhile, in the process like the furnace where the atmosphere temperature is maintained with the gas' heating value atmosphere, temperature decrease accompanies the heating value decrease so an automatic temperature control device such as TIC is necessary.

4) It was confirmed that in the metal industry processes such as the thermal process was very sensitive to the heating value where the natural gas is not used as the fuel but as the raw material. This change of natural gas heat value change represents the change of raw materials' stoichiometric ratio and it is a phenomenon that is caused by the oxidation/reduction atmosphere change similar to the thermal process.

5) In the case of natural gas automobiles, the automobiles were all able to be driven under the basis of rules of the motor vehicle safety standard in all types of the experiment gases but the 5% and above output and gas mileage decrease could be a problem so this study proposes the consideration that it is preferable the heat value decrease limit be at the maximum within 6%.