Additional information about the equation described in the methodology to calculate energy efficiency of burners

Generally energy efficiency can be defined as the ratio between quantity of input energy and utilized energy.
In the same manner, energy efficiency of burners in the proposed methodology can also be calculated by “the quantity of energy which the burners actually utilize for generating heat, divided by the quantity of energy input into the burners”.

- “quantity of energy input to the burners” is derived from “total calorific value of natural gas input to the burners”
- “quantity of energy utilized by the burners for combustion” is derived by subtracting “the calorific value contained in the exhaust gas” and “the calorific value contained in excess air” from “the total calorific value of natural gas input into the burners”

Therefore, the following equation is applied to calculate energy efficiency of burners in the proposed methodology.

Calorific value contained in the exhaust gas

Calorific value contained in the excess air

$$\eta = \frac{NCV_{NG} - [Gw_{NG} * c_1 * (T_1 - T_2) + A_{0,NG} * (m - 1) * c_2 * (T_1 - T_2)]}{NCV_{NG}}$$

Total calorific value of natural gas input to the burners

In case of regenerative burners, energy efficiency of burners approaches to 100% (η=1) if the temperature of exhaust gas and excess air becomes closer to that of the ambient temperature by heat exchange between exhaust gas/air and inlet gas/air.

Default values for each parameters of the equation are set by selecting conservative values and referring to the values published by the IPCC and the Japan Industrial Standards.

[Key assumptions for the establishment of default efficiency]

Typical composition of natural gas, according to the published IPCC’s document

"Properties of CO_2 and carbon-based fuels", contains 98.4% of hydrocarbon (CnHm) as shown in the following table.

Table Typical composition of natural gas

Component	Ratio
	Mol% (dry)
Carbon dioxide CO_2	0.5
Nitrogen N_2	1.1
Methane CH_4	94.4
Ethane C_2H_6	3.1
Propane C_3H_8	0.5
Isobutane C_4H_{10}	0.1
N-butane C_4H_{10}	0.1
Pentanes+ (C_5+)	0.2
Hydrogen sulphide (H_2S)	0.0004
Helium (He)	0

Source: IPCC "Properties of CO_2 and carbon-based fuels"

When natural gas is combusted with burners, components of natural gas and air react and are released as exhaust gas, where hydrocarbons (and other substances) in natural gas are oxidized. Typically, excess amount of air is pumped into the furnace than the amount which is needed to fully oxidize the natural gas (by a few percentage points) in order to avoid incomplete combustion. Therefore, energy is transported out of the furnace in the form of heat contained in exhaust gas and excess air.

[Calculation of quantity of calorific value contained in the exhaust gas]

Four parameters are required to calculate the calorific value contained in the exhaust gas;

1. Gw: Theoretical volume of wet exhaust gas generated from combustion of natural gas [Nm^3/Nm^3]
2. c_1: Average specific heat at constant pressure of wet exhaust gas generated form combustion of natural gas, at specific temperature of exhaust gas [kJ/ Nm^3・degree Celsius]
3. T_1: Temperature of exhaust gas [degree Celsius]
4. T_2: Ambient temperature [degree Celsius]

1. Gw: Theoretical volume of wet exhaust gas from combustion of natural gas

- Combustion equation ($C_mH_n + (m+n/4)O_2 \rightarrow mCO_2 + (n/2)H_2O$) provides the theoretical amount of air, dry exhaust gas and wet exhaust gas.
  - i Theoretical amount of air = (m+n/4)/0.21
    Theoretical amount of air is the minimum volume of air required for complete combustion of fuel. Since oxygen is required for combustion, theoretical amount of air can be derived from dividing the total volume of oxygen by the ratio of oxygen to air (21% in volume, 23.2% in mass).
  - ii Volume of dry exhaust gas = Theoretical amount of air*(1-0.21)+m
    Dry exhaust gas is a gas resulting from complete combustion of fuel. Volume of dry exhaust gas is summation of gases other than oxygen consumed at combustion and carbon dioxide generated by combustion.
  - iii Volume of wet exhaust gas = Volume of dry exhaust gas+(n/2)
    Volume of dry exhaust gas is summation of dry exhaust gas and vapor generated at combustion.
- Since natural gas usually contains four types of hydrocarbon (CH_4, C_2H_6, C_3H_8, C_4H_{10}), theoretical amount of air, volume of dry exhaust gas and volume of wet exhaust gas can be calculated from the corresponding volumes of each hydrocarbon combusted and their composition ratio.
- E.g.
  a. Theoretical amount of air = 9.69 m^3
  b. Volume of dry exhaust gas = 8.68 m^3
  c. Volume of wet exhaust gas = 10.69 m^3
  d. Total volume of exhaust gas = Volume of wet exhaust gas + Volume of gases other than hydrocarbon = 10.71 m^3

2. c_1: Average specific heat at constant pressure of wet exhaust gas generated form combustion of natural gas, at specific temperature of exhaust gas

- Average specific heat at constant pressure of wet exhaust gas generated form combustion of natural gas can be derived from Appendix Table 2 “linear prediction is used for the estimation” of “JIS G 0702:1995 Method of heat balance for continuous reheating furnace for steel”.
- Average specific heat of natural gas can theoretically be derived from the specific heat of four types of hydrocarbon (CH_4, C_2H_6, C_3H_8, C_4H_{10}) and their composition ratio.

- Although the temperature of exhaust gas temperature of reference burner is set as 750 degree Celsius in the methodology, the Appendix Table 2 only shows data at every 100 degree Celsius. Therefore, theoretical value (1.481kJ/Nm^3) is derived from averaging two specific heat values of 700 degree Celsius and 800 degree Celsius.

3. T_1: Temperature of exhaust gas
   - Temperature of exhaust gas in the methodology is set in a conservative manner (please refer "ADDITIONAL INFO FOR REFERENCE EMISSIONS")

4. T_2: Ambient temperature
   - Annual average ambient temperature in Jakarta is adopted in the methodology.

[Calculation of quantity of calorific value contained in the excess air]

Five parameters are required to calculate the quantity of heat contained in exhaust gas;

1. A_0: Theoretical amount of air of natural gas [Nm^3/Nm^3]
2. m: Air ratio for burner
3. c_2: Average specific heat at constant pressure of air, at the specific temperature of exhaust gas [kJ/Nm^3・degree Celsius]
4. T_1: Temperature of exhaust gas [degree Celsius]
5. T_2: Ambient temperature [degree Celsius]

1. A_0: Theoretical amount of air of natural gas
   - Theoretical amount of air of natural gas can be derived with the same method as the calorific value contained in exhaust gas, which is 9.69m^3.

2. m: Air ratio for burner
   - As a practical matter, air more than theoretical amount is required for stable combustion. The recommended operational value in the manual of the actual burner or the default value set as 1.05 in case of the reference burner can be selected in the methodology in a conservative manner.

3. c_2: Average specific heat at constant pressure of air, at the specific temperature

of exhaust gas

- Average specific heat at constant pressure of air can be derived from Appendix Table 2 “linear prediction is used for the estimation” of “JIS G 0702:1995 Method of heat balance for continuous reheating furnace for steel”.
- E.g. Average specific heat of air at 750 degree Celsius is almost equal to 1.380kJ/Nm^3

Rationale for deriving parameters of 4. and 5. is the same as those mentioned above for the exhaust gas.