Development of NG Fueled Steel Cutting Torch for Industrial Application.

Hyun-Seok You, Korea Gas Cooperation Research & Development Div.
Jeong-Ok Han, Korea Gas Cooperation Research & Development Div.
Sang-Keun Dong, Korea Institute of Energy Research

1. Introduction

For a steadfast management of natural gas (NG) demand and its further extension, creating new industrial demands is more beneficial, which requires technical development for many industrial applications. In this perspective, the application area of NG cutting for industrial steel needs technical development, where it has relatively inferior burning characteristics (in terms of heating value, burning speed, and straightness of the flame etc.) compared to existing ethylene, acetylene, and LPG, leading to poor conditions in the cutting process.

Lack of handling safety and high cost of the existing fuel for cutting process have been pointed out as demerits; especially for a large scale business it uses ethylene, acetylene and LPG for cutting process and also needs NG for heating source of boiler and furnace, failing to centralize energy sources of the manufacturing sites letting them to wish technical development to utilize NG also for the cutting processes.

Design technology of torch for NG cutting process has reportedly been developed by countries including Germany and Japan, but it has rare cases of practical applications; especially, the techniques for cutting over 1000mm thick steel is very unreliable and there are no reported successful applications of cutting up to 2000mm thick steel.

Therefore, this study intended to acquire optimization design technology for NG cutting torch by numerical analysis and verification test, and developed a torch that can cut steels with thickness ranging from 400mm to 2000mm.

2. Theoretical background

2.1 Principle of oxy/fuel gas cutting

The oxy/fuel gas cutting (OFC) is a cutting method that utilizes chemical reaction of oxygen and iron. This method preheat cutting area to reach 800-900 °C by oxygen fueled flame coming out of the tip around, and then high pressure cutting-oxygen blows through the center of the tip, burn iron, leaving oxidized iron, which cuts by melting itself because of its low melting temperature compared to
iron. Oxidization of iron in cutting process is thought to produce heat by thermo-chemical reaction as the following.

\[ Fe + \frac{1}{2}O_2 \rightarrow FeO + 63.8\text{Kcal} \]
\[ 2Fe + \frac{1}{2}O_2 \rightarrow Fe_2O_3 + 96.8\text{Kcal} \]
\[ 3Fe + 2O_2 \rightarrow Fe_3O_4 + 267.8\text{Kcal} \]

OFC is a process that brings about cutting or removing of metal by chemical reaction of pure oxygen and metal at a preheat temperature. Actual cutting of metal is accomplished by pure oxygen flow, where the oxygen fuel flame just takes the role to elevate the preheat temperature of the cutting metal to a proper level for oxidization and maintain it to sustain the cutting process.

The torch functions to form a preheat flame out of a precisely proportioned mixture of oxygen and gas, and supply a concentrated flow of a highly purified oxygen evenly to the reaction area. The oxygen flow oxidizes the preheated metal and actually blows away the molten oxide out of the cutting area as well. Condition of the cut surface is determined by flow characteristics of the cutting oxygen.

Drag, kerf, and cutting speed are the factors that determine the cutting performance. Drag refers to curves formed in the direction of the cutting-oxygen flow, which is caused by moving torch faster than the cutting capacity. Kerf represents the ratio of cut width at the top to the bottom, the larger value of which degrades the product quality. And cutting speed means torch moving velocity. Hence, drag and kerf relate to the cut product quality, and the cutting speed to the production volume.

### 2.2 Analysis of combustion model

This study performed numerical analysis of flow and burning field using the commercial FLUENT code to setup theoretical background and systematize indigenous design technologies. The most relevant combustion model among existing turbulent combustion models was selected, which is suited to the numerical analysis of this study.

The Magnussen model applicable both to diffusion and premixed flame relating reaction rate to eddy lifetime \((\varepsilon / \kappa)\) was used.

\[ R_{fu} = -\rho \varepsilon \frac{\kappa}{\kappa} \text{MIN}(Am_{fu}, Am_{pr}, D_{fu}) \]

Here, \(Am_{fu} + Am_{pr} + Am_{tru} = 1\), \(A=32\), \(B=4\), STOIC. = stoichiometric value.

Also, \((\varepsilon / \kappa)\) and \(R_{fu}\) were set to include streamline curvature effect and \(R_{CO}\) was applied to the above model as well. A combustion model should accompany a reaction relation, for which this study utilized the following two-step global model to compute CO concentrations.

\[ C_xH_y + \left(\frac{x}{2} + \frac{y}{4}\right)O_2 \rightarrow xCO + \frac{y}{2}H_2O \]
\[ xCO + \frac{x}{2}CO_2 \rightarrow xCO_2 \]
By solving a transfer equation \( m_{fu}, m_{CO}, m_{CO_2}, m_{O_x} - im_{fu}, m_{no} \), the rest chemical species is obtained from a reaction relation as above by using an equilibrium equation. Here, \( i \) means a stoichiometric value.

\[
i = \frac{32\left(\frac{x}{2} + \frac{y}{4}\right)}{12x + y}
\]

### 2.3 Flow analysis in the nozzle

To acquire design values for cutting-oxygen velocity and flowrate, which are critical factors in cutting, the supplied pressure of cutting-oxygen should be taken as a reference value. As the exit of cutting-oxygen is subject to atmospheric pressure, pressure drop from inside the torch through the inlet and onto the outlet of the nozzle needs to be verified to determine operational conditions or decide cutting possibility comparing the supplied pressure of nozzle with the required pressure level for cutting. Here, the pressure drop from where supplied pressure is measured through the flow line leading to nozzle varies, because the length of the line differs from site to site; the pressure drop can be neglected. Pressure drop is caused by friction, which is the function of the square of flow velocity where again the flow velocity is approximated by root square of the flow line diameter, and the friction coefficient itself is inversely proportional to the line diameter. Therefore, comparing the diameter of the nozzle with that of the line, the pressure drop in the line comes out to be negligibly small compared with that in the nozzle.

Configuration around the nozzle for analysis is as the following.

**Fig.1 Flow line configuration of the cutting-oxygen nozzle**

- \( D_1 \): cutting-oxygen passage diameter in the nozzle
- \( D' \): nozzle inlet diameter
- \( D_2 \): nozzle outlet diameter
- \( D \): constant nozzle duct diameter
- \( L \): nozzle duct length with constant diameter
- \( V_1 \): cutting-oxygen velocity around torch
- \( V_2 \): cutting-oxygen velocity at nozzle outlet
- \( V \): cutting-oxygen velocity at nozzle duct with constant diameter
- \( P_1 \): pressure in the torch
- \( P_i \): ideal pressure in the torch
As shown in the figure, flow line is contracted in cross-section at the nozzle inlet, a constant section is maintained pass the nozzle and is finally expanded leading to a supersonic nozzle flow. The flow is supersonic and the fluid is compressible, hence a consistency of thermal properties is important for a numerically accurate computation to come out. However, the thermal properties are hard to measure and hardly produce a consistent calculation result. Therefore, the pressure drop was separately accounted for by the pressure change in an isentropic process without loss and an irreversible loss.

3. Experimental methods and equipments

3.1 Experimental methods

This study of LNG torch development methods focused on improving shortcomings of LNG such as low heating value (2.3 times lower than LPG) and fast diffusion in contrast to LPG. To make up for these demerits, separate designs with symmetric nozzle arrangement and unsymmetrical nozzle arrangement were prepared.

The unsymmetrical one is designed to form an unsymmetrical jet of oxygen and fuel gas in the direction of cutting. This is to concentrate the flame on one side compensating for the relatively low straightness of the NG flame. But in the case of cutting circular shape, the unsymmetrical nozzle is not applicable, therefore an alternative method was sought which can increase concentration in the direction of the fuel gas jet. For this, the methods to increase flow force of stream by adding the cutting-oxygen velocity and improve concentration of oxy/fuel flame to the core were investigated.

The nozzles designed based on these concepts were estimated by numerical analysis for their performances, and the nozzles producing favorable results were put to actual tests in sites to verify cutting performances. Because on-site measuring of the gas flow rate for operation was not possible, the test was conducted based on pressure estimated through flow calculation for inside of the nozzle. An optimum pressure was verified in this test. Fig.2 represents calculation results for each developed nozzle, showing relation between the pressure of cutting-oxygen and the flow rate.

![Fig.2 Relations between pressure drop and flow rate of cutting-oxygen for each developed nozzle](image-url)
3.2 Experimental equipments

A total of six new nozzles were designed and fabricated in this study. Developed nozzles including the existing LPG nozzle were named M2-1, M2-2, M2-3, M2-4, M3-1 and M3-2. Among these, LPG nozzle and M2 series nozzles are horizontally symmetric and M3 series nozzles are unsymmetrical. Larger number in the subscript means larger diameter of the cutting-oxygen flow, where nozzles for preheat oxygen and fuel have constant diameters. Nozzle lengths of LPG, M2-4 and M3-2 are 100mm and others are 80mm long.

The place for on-site test was at a manufacturing company producing large ship engines. Cutting thickness ranged from 400mm to 2000mm and the material was supplied on the site. Because of the large volume of the material, moving of the cutting torch was conducted by programming in an exclusive operated NC machine.

4. Results

4.1 Results of numerical analysis

Fig.3 represents results with LPG nozzle (for cutting 1500mm-2000mm) using NG as the fuel, which is intended to compare with a newly designed LNG nozzle. Here, the inlet velocity of cutting-oxygen is 611m/s and that of fuel gas is 184m/s. The look of the temperature field reveals a typical oxygen-fuel flame, which verifies the calculation results. The velocity field readily shows the highest velocity at the center of the cutting nozzle and wide growth of diffusion area at the rear. Looking at the methane mole fraction, which tells the extension of burning reaction band, it can be estimated that the reaction band is relatively short and spreading in the direction of the nozzle radius. Therefore, developed nozzles should have the function to minimize diffusion at the rear and the extension of the reaction band.

Fig.4 represents the nozzle M2-1 (900-1200mm) with 1081 m/s cutting-oxygen inlet velocity and 64m/s fuel gas inlet velocity, for which it can be estimated that the flame intensity is more concentrated to the center and the structure of the nozzle allows more chance of shedding compared with LPG nozzle, however the oxygen flow at the front head of the nozzle is estimated to be very straight. This is the result of adding flow force of the oxygen stream by increasing the cutting-oxygen velocity, and concentration of the preheat gas jet flame to the core.

Fig.5 represents the nozzle M2-2 (1200-1500mm) with 795m/s cutting-oxygen inlet velocity and 64m/s fuel gas inlet velocity, and it is shown that the flame is concentrated to the center, with excellent straightness and flame formation without shedding at the rear.

Fig.6 represents the nozzle M2-3 (1500-2000mm) with 692m/s cutting-oxygen inlet velocity and 64m/s fuel gas inlet velocity, which shows the flame concentrated to the center and the oxygen jet with excellent straightness, although with slightly narrower flame width compared with the M2-2, caused by the increase of flame concentration at the core; and general characteristics of the nozzle revealed
much closeness to M2-2. When compared with the results of LPG nozzle that can cut the same thickness, it can be estimated that flame straightness and concentration at the core are quite improved.

Fig.7 represents the nozzle M2-4(1500-2000mm) with 692m/s cutting-oxygen inlet velocity and 64m/s fuel gas inlet velocity, which shows a longer reaction band compared with M2-3; especially the oxygen flow is more improved. The M2-4 model is the succeeding model of the M2-3 model with increased nozzle length and improved nozzle structure.

Fig.8 represents the nozzle M3-2(1500-2000mm) with 741m/s cutting-oxygen inlet velocity and 180m/s fuel gas inlet velocity, which shows a flame unsymmetrically skewed and with a steady formation slightly above the center. And also, the nozzle showed a burning reaction band formed longer, narrower and higher, suggesting that it is more efficient to preheat the cutting steel compared with LPG nozzle. Telling from the oxygen mole fraction diagram, the nozzle shows narrower jet formation compared with LPG nozzle implying that it is more efficient to remove the non-oxidized steel by oxygen jet, and also, considering the velocity magnitude, it showed longer extension reaching to the rear.

Fig.3 Calculation result for applying NG to LPG nozzle(1500-2000mm)
Fig. 4 Calculation results of the nozzle M2-1(900-1200mm)
Fig. 5 Calculation results of the nozzle M2-2 (1200-1500 mm)

Fig. 6 Calculation results of the nozzle M2-3 (1500-2000 mm)
Fig. 7 Calculation results of the nozzle M2-4 (1500-2000mm)
4.2 On-site experimental results

Based on the numerical analysis results, verification test was performed applying the nozzles. Nozzle M2-3 was successful in cutting a 2000mm thick of actual product. But the nozzle length was 80mm, shorter than the existing LPG nozzle by 20mm, which exposed the nozzle to the possibility of overheat by the heat produced from oxidizing reaction. And also, an occurrence of drag was observed at the lower end portion of the steel.

Cutting test was performed for M2-4 nozzle and M3-2 nozzle, newly designed, to improve the drag on the cutting surface that occurred using M2-3 nozzle. Operation condition was the same as that for the M2-3 nozzle. Flame formed at nozzle M2-4 reveals excellent flow of oxygen at the rear portion, and with the nozzle M3-2, an ejection flow of oxygen was seen to form strongly at the head portion of the nozzle. From the look of the non-oxidized steel being blown away at the bottom, M3-2 appeared stronger than M2-4 with low kerf due to flame shape and larger cutting width at the top. The surface cut with M2-4 nozzle proved to be excellent with 100mm drag. Although, the cutting surface was rather rough for M3-2 owing to the strong oxygen flow, it made up for LNG's shortcoming of having insufficient heating value for the case of thick plate cutting; it also showed a drag of 50mm, which represents that it has superior cutting capacity as compared with M2-4. Therefore, numerically estimated M2-4 and M3-2 improved in straightness of the flame better than M2-3 and also showed excellent jet flow of the cutting-oxygen consistent with the test results.

To verify the versatility of the developed M2-4, M3-2 nozzle, cutting test with 1600mm mother steel was performed. As for M2-4 nozzle, the drag was 70mm at best and cutting width was 20mm for the top and 30mm for the bottom. M3-2 nozzle showed maximum of 30mm drag and 30% more of the cutting width compared with M2-4. These results indicate closeness to the results of cutting 2000mm thick steel.

Putting all the test results above together, it can be said that M3-2 has 30% wider cutting width than M2-4. And measured kerf values ranged from 1.5 to 2 presenting no problem in the application of
LNG torch to the field. Although not described in this paper, nozzle M2-1 showed excellent performance for cutting 900-1200mm and M2-2 was successful in cutting 1200-1500mm.

Fig.9 shows moving speed of oxygen/NG gas cutting nozzle subject to thickness variation of steel. This was based on cutting speeds used in sites and generally favored by customers. Here, a commonly used steel with more than 0.3% carbon composition was chosen for reference material. On the average, the velocity reduction was not less than five to seven percent as against LPG or ethylene, which is a reasonable amount for application.

![Graph showing cutting speed vs. thickness](image)

**Fig.9 Cutting speed for oxygen/NG nozzle**

5. Conclusion

This study conducted development of NG torch for steel cutting, and reached the following conclusion.

1) NG compared with formerly used LPG for cutting process revealed high diffusion and low heating value confirming that the existing torch increases kerf and drag of the cutting surface and leads to a poor working.

2) As for developed nozzle, the increased flow force of the oxygen stream was acquired by adding the cutting-oxygen speed, and with the jet formation of preheating fuel and oxygen, kerf and drag was successfully minimized by improving the flame concentrating power.

3) Applying the Magnussen combustion model to the numerical analysis of oxygen/NG cutting flame, the burning field showed very close results to the proof test results.

4) Optimum operation conditions were extracted for M2-1(900-1200mm), M2-2(1200-1500mm), M2-4 and M3-2(1500-2000mm) based on flow field analysis in the nozzles and cutting velocities only five to seven percent less than using LPG was obtained.
5) Study results was applied to a company manufacturing engines for large ships, eventually producing new demands for NG.

REFERENCES