# Continuous combustion flame of Egyptian pulverized coal using cyclone burner

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Finally, stable flames of Egyptian pulverized coal using cyclone tube burner is achieved. The cyclone tube burner is composed of refractory materials. Its inner diameter 10 cm and length 50 cm, one of the tube ends is blocked with refractory materials and the other end is kept open free to the atmospheric air. The burner is provided with five tangential inlet passages; four of them are used to supply spiral streams of compressed hot air while the fifth passage is used to feed the mixture of the pulverized coal and carrier air. In order to create strong turbulent vortex of the combustion hot air and the coal particles, the passages are drilled with inclination of 30° to the perpendicular plane to the burner axis. The burner axis is deflected 5° with horizon toward the free exit end to drain the coal-slag. By switching on the electrical heaters, both of the burner refractory and the compressed combustion air are heated up. When the combustion air temperature reaches 450°C the electrical heaters are switched off and the mixture is fed from the coal feeder into the burner tube through the fifth passage. The coal particles begin to devolatilize producing hydrogen-rich volatiles and tar which are important for ignition and flame stability. The achieved continuous flame is stable, smokeless and has a golden-red colour. Also, the coal-slag is found to be sufficiently mobile and its deduced silica ratio is found to be 72%.

تم تصميم وبناء حارق أسطوانى دوامى وذلك بغرض الحصول على لهب مستمر ومستقر ناتج من أحتراق مسحوق الفحم المصرى البيتوميني والمستخرج من المغارة بسيناء. ماسورة الحارق مصنوعة من مواد حرارية بقطر داخلى ١٠ سم وطول ٥٠ سم. أحد طرفى الماسورة تم سده بالمواد الحرارية والطرف الأخر ترك مفتوح للهواء الطلق. الماسورة تميل بمقدار ٥ درجات مع الافقى جهة الطرف المفتوح. عند الطرف المسدود تم عمل أربع فتحات بقطر ٤ مم تسمح بدخول هواء الاحتراق المضغوط بشرط أن تكون الفتحات الاربع متعامدة على بعضها البعض وتكون مماسة للجدار الداخلى للماسورة وأن يكون محور كل منها يصنع ٣٠ درجة مع المستوى العمودى على محور ماسورة الحارق وذلك لضمان تدفق الهواء للخارج فى مسارات حلزونية (دوامية) وملاصقة للجدران الداخلية لماسورة الحارق. كما أضيف فتحة خامسة بنفس مواصفات الفتحات السابقة وملاصقة لأحدهم لكى تسمح بتدفق الخليط (الفحم المسحوق + هواء الحمل) القادم من مغذى الفحم. تم عمل ممرات خارجية فى الماسورة لكى يدفن فيها أسلاك كهربائية حرارية تستخدم فى تسخين هواء الاحتراق داخل الماسورة وكذلك هواء الاحتراق المضغوط والذى يمر عبر أنبوب نحاسى ملفوف حول الماسورة من الخارج وذلك قبل أن يتشعب الآنبوب ويدخل لماسورة الحارق عبر الفتحات الأربع السابقة. عند بداية التشغيل يتم تسخين ماسورة الحارق بتوصيل الكهرباء الى ملفات التشخين وكذلك يسمح بتدفق الهواء المضغوط الى داخل الحارق عبر الاربع فتحات. وعندما تصل درجة حرارة الهواء داخل الماسورة ٤٥٠ درجة مئوية تفصل الكهرباء ويسمح بتدفق الخليط عبر الفتحة الخامسة فتنطلق أبخرة المواد المتطايرة من حبيبات الفحم المسحوق والتى تشتعل مكونة ألسنة لهب ملتصقة بالأسطح الداخلية لماسورة الحارق. ويستمر أحتراق حبيبات الفحم نتيجة انتقال الحرارة المسترجعة من الحبيبات المحترقة الى الحبيبات الطازجة . وبذلك تم الحصول على لهب مستمر ومستقر لونة ذهبى محمر وبدون هباب. كما تم دراسة تأثير تغيير قطر مخرج ماسورة الحارق على مستوى الاحتراق وطول اللهب ودرجة الحرارة عند مخرج الحارق وكذلك حجم منطقة التدفق المركزى المعكوس. كذلك وجد ان خبث الفحم المصرى له خاصية الحركة والأنتقال حيث وجد أن نسبة السيليكا عند ظروف التشغيل ٧٢ %.

**Keywords:** Pulverized coal, Cyclone burner, Continuous flame, Slag mobility

## 1. Introduction

It is more difficult to burn coal in a confined space. It is the challenge of coal combustion researches to develop technologies to burn coal efficiently and cleanly [1]. The work on cyclone combustion began in latter part of 1920 as part of a program of research into solid fuel firing for gas turbines, carried out by the British Coal Utilization Research Association (BCURA). Cyclone combustors were developed by Babcock and Wilcox in the

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USA in the 1944s [2]. Many special design problems such as: Thermal ignitability, diffusion flame stability and special direction and velocity relations are needed between the primary air and secondary air to prevent erosion of combustion chamber linings by the rough crushed coal. Also, liquid ash is deposited on the lining, and, upon the heating, on tube surfaces and tends to cause corrosion, erosion and blockage. Thus, the fusibility and viscosity of the fuel ash are important factors [3-4]. Many investigations had been done on coal combustion characteristics [5-10] and pulverized coal and char [11-14]. Combustion of Anthracite coal [15], pulverized lignite and Bituminous coals were investigated [16]. The higher volatiles content in Lignite leads to higher temperature and more intense combustion [17].

This work is concerned with the study of combustion and stability of Egyptian Sub-Bituminous pulverized coal and reliability of the cyclone burner. Many trails are done in order to provide steady flow of the pulverized coal particles and to achieve a continuous stable flame. Also, Coal-slag mobility is investigated.

## 2. Experimental set up and instrumentation

The experimental arrangement consists of the following main components: 1) cyclone tube burner, 2) electrical heaters, 3) compressed hot air lines, 4) pulverized coal feeder, 5) sampling system as shown in fig.1.

The cyclone tube burner is composed of refractory materials. Its inner diameter 10 cm and length 50 cm, one of the tube ends is blocked with refractory materials and the other end is kept open free to the atmospheric air. The tube is provided with five tangential inlet passages 2 cm away from the blocked end, four of them are used to supply hot compressed combustion air while the fifth passage, which is adjacent to one of the four passages, is used to feed the mixture (pulverized coal particles and compressed carrier air). The passages are drilled such that their outlet ports, 4 mm diameter, are tangent to the inner surface of the tube and each passage direction is perpendicular to each other. In order to create strong turbulent vortex of the combustion hot air and the coal particles moving the streams toward the burner exit, the passages are drilled with inclination of 30° to the perpendicular plane to the burner axis. The burner axis is deflected $5^{\circ}$ with horizontal toward the free exit end to drain the coal-slag.

6 KW electrical heaters wires are installed in order to heat up the air inside the cyclone tube. The wires are parried into longitudinal notches which are formed in the outer surface of the cyclone tube. To double the heating effect, the compressed combustion air is directed to passé through a copper tube which is coiled around the electrical-heater. Consequently, the compressed combustion air absorbs heat and became hot before it branched off to the four streams which pass through the four tangent passages. Fore more efficient heating, the copper coil is covered with a thermal insulator.

In order to investigate the effect of changing the free end diameter -burner exit diameter- on coal particles combustion, discs with different holes diameters 27, 39, 50, 67, and 100 mm are fixed in turn at the free end of the tube.

It was not easy to maintain constant flow rate of the pulverized coal particles, many trails were done to overcome this problem. A simple laboratory fluidized bed elutriation feeder [18-19] is designed and developed to provide a uniform and stable flow of the Egyptian pulverized coal particles without compaction, degradation or segregation of the coal particles. The feeder system construction is shown schematically in fig. 1. During operation, the transparent off-take tube is screwed downwards with a calibrated displacement rate towards the stationary vessel containing the feed coal particles. A small flow of carrier compressed air is introduced into the bottom of the feed-vial through a bronze filter to promote uniform entrainment and also to prevent compaction of the feed coal. In the apex of the inverted cone of the off-take tube the feed materials (coal particles and compressed carrier air) transported to the cyclone burner via a small diameter flexible tube. The inverted cone was fixed in the off-take tube. The screwed

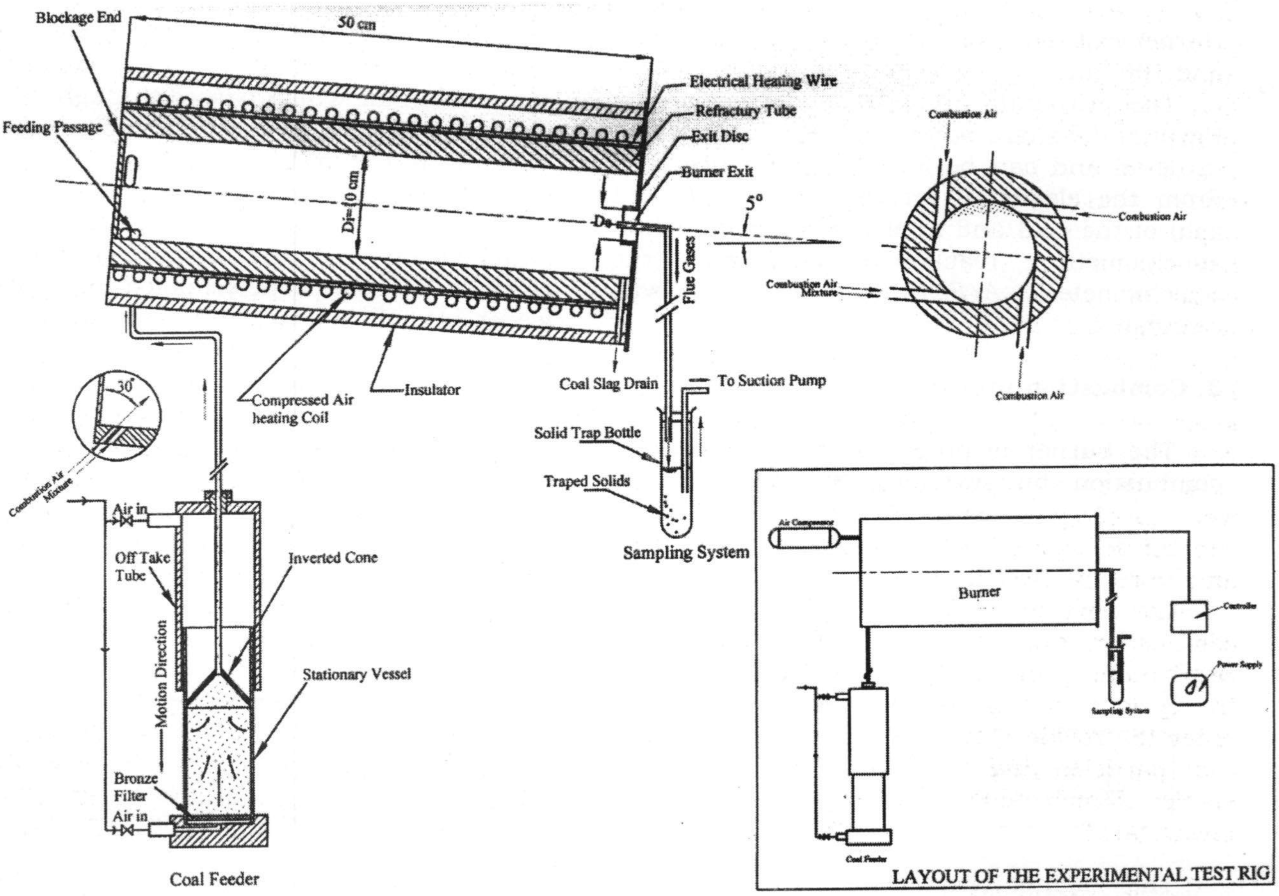


Fig. 1. Experimental test rig arrangement.

downwards displacement was calibrated with the coal flow rate by weighting the coal particles before and after a certain time and adjusting downwards displacement rate repeating these procedures until a constant coal flow rate was obtained. To check the rate, the coal was weighting before and after every run.

The solid samples of partially or completely burnt coal particles are extracted using a rapid quench water-cooled sampling probe, which is operated at an appropriate suction velocity. The solid samples are retained and trapped in Quick fit-wash bottle, whilst the flue gases are drawn through a flexible plastic tube to a suction pump. The sampling period is about 5 minutes.

The local air and gas temperature is measured by using Pt and Pt-Rh 13% wires thermocouples.

Oxygen concentration measurements have been conducted through a gas sampling system using a gas analyzer model TESTOTERM-350.

The reverse flow zone boundaries are determined by using two-hole probe detector.

The coal lump is crushed, ground, and dry sieved according to American standard in the laboratory of Faculty of Engineering, Port-Said, Egypt. The experimental operating conditions were as follows:

The particles mean diameter = 120 µm.
Coal feeding rate = 1.2 gm/s,
Combustion air flow rate = 13.5 gm/s,
Stoichiometeric *A*/*F* ratio =9.374 $Kg_{air}/Kg_{coal}$
Actual air/fuel ratio =11.25 $Kg_{air}/Kg_{coal}$
Excess air factor = 20 %
Combustion air temperature = 450 °C

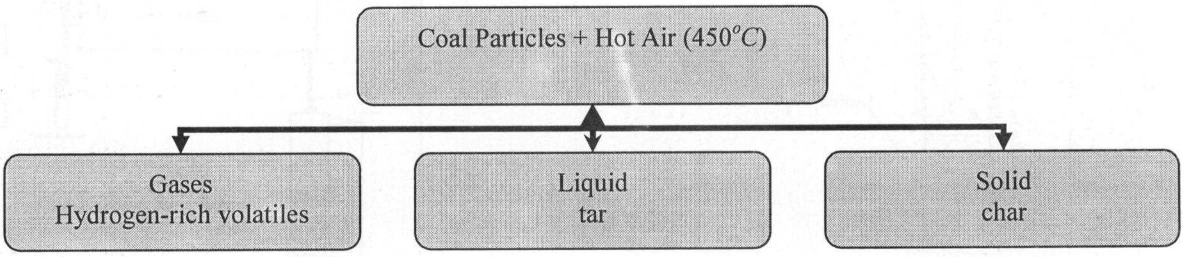
Burner exit diameters (De) = 27, 39, 50, 67, and 100 mm.

The proximate and elemental analysis of Egyptian Maghara parent coal was determined in detail and can be found in reference [16]. From the elemental analysis (C, H, $O_2$ and ash) of the coal and applying the combustion stoichiometrc reaction equations, the Stoichiometeric $A/F$ ratio of the coal was calculated.

## 3. Combustion proceeding

The burner is prepared for coal particles combustion by switching on the electrical heaters in order to heat up both the burner refractory tube and the compressed combustion air which passes through the four tangent passages forming four spiral streams tangent to the inner surface of the burner tube. When the combustion air temperature reaches $450^{o}C$ the electrical heaters are switched off and the mixture (compressed carrier air + coal particles) is fed from the coal feeder into the burner tube through the fifth passage.

The coal particles begin to devolatilize producing hydrogen-rich volatiles and tar which are important for ignition and flame stability.



The lighter volatiles released firstly upstream the burner and mixed with the hot combustion air, consequently combustion commences. The majority of the coal particles flung to the burner wall where gasification continue and start to burn there forming spiral flame tangs which anchored at the interior surface of the cyclone tube burner as shown in fig. 2. The feed back heat is responsible for the heating and devolatilization of the fresh coal particles, so reactions continue. The volatile reaction is very rapid [20] in comparison to overall burning rate of the coal particles. The lighter volatiles are burnet mainly, inside the tube of the burner while the heavier volatiles, tar, and char continue their reaction outside the burner tube. A significant lighter volatile fraction is ejected from the coal particles as jets [21]. These volatiles jets react close to the coal particles producing heat, in combination with heterogeneous reaction, which increases the particles temperature and raises it above that of the bulk gas stream [20]. The residue fuel(s) in particular coal-char complete their burn out of the burner tube forming a stable flame. The char reaction is dominant phenomenon in the downstream zone, where incandescent particles appears.

In order to check the ignition temperature limit of the coal the combustion air temperature is reduced down to 400°C. It is found that no combustion occurs but heavy volatiles matters with brown colour are released and discharged from the burner tube exit accompanied by coal-char as shown in fig. 3. Increasing the air temperature to $450^{o}C$, a continuous flame is obtained replacing the evolved volatiles matters as shown in fig. 4. The coal particles flame is stable, smokeless, hollow, golden-red colour and extended outside the burner. Continuous flames with different shape and size are obtained according to the change of the exit diameter ratio as shown in fig. 5.

The running designed burning system is proved to be suitable to provide continuous combustion flame of Egyptian pulverized coal.

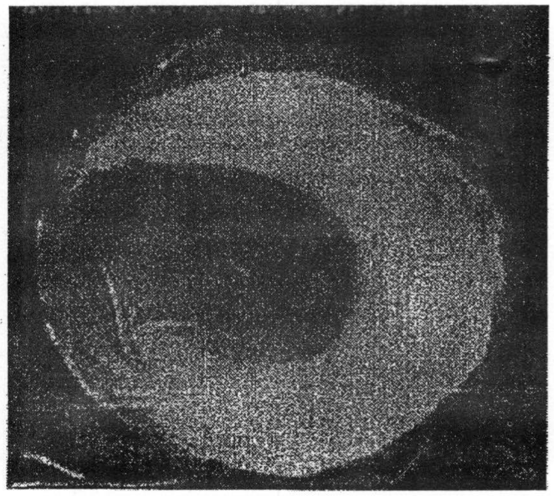


Fig. 2. Flame tang anchored at the interior surface of the burner.

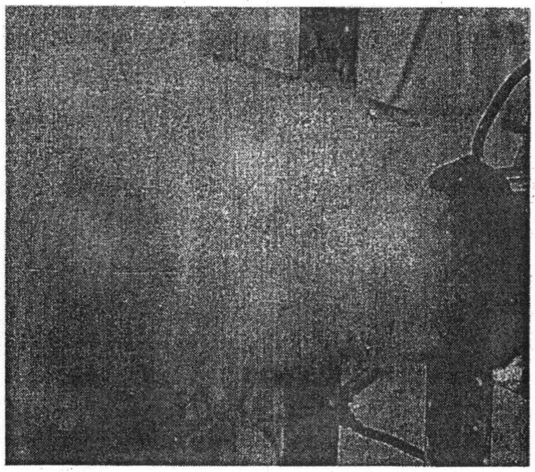


Fig. 3. Release of volatile matters at 400°C.

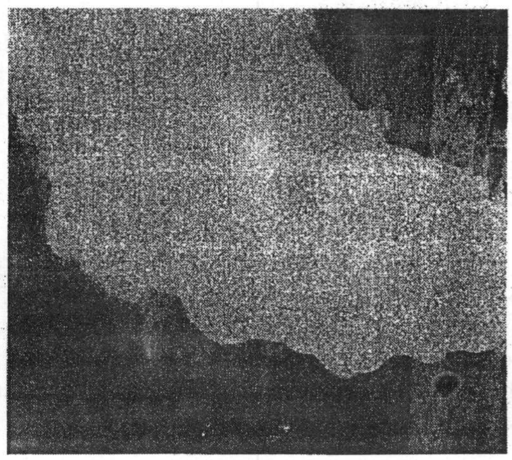


Fig. 4. Continuous flame of pulverized coal combustion.

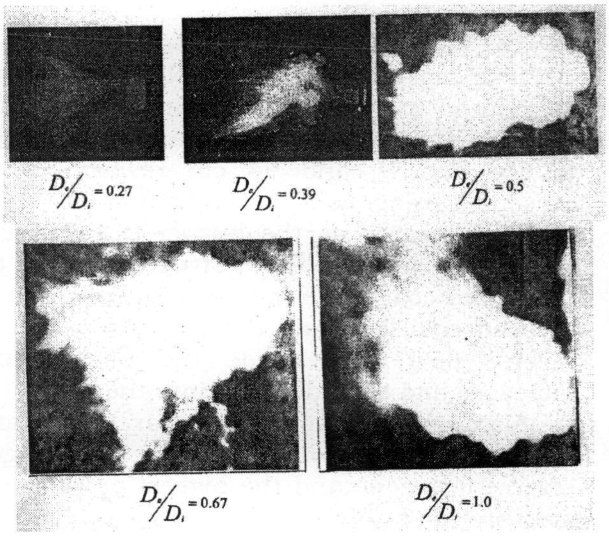


Fig. 5. Continuous flame of pulverized coal combustion at different exit diameter ratio ($D_e/D_i$).

## 4. Performance of the coal particles burner

The effect of changing the burner exit diameter on: total combustion level, flame length, and gases temperature is investigated. Solid samples are collected at two different places; at the end of the burner exit and at the end of the visible flames. These samples are ashed (using ash as a tracer) in order to determine the mass loss percent of the solid combustible materials of the coal particles as a result of devolatilization and char reactivity as follows [20-22]:

$$\text{Combustion Level} = \frac{\left(1-\frac{A_o}{A}\right)}{(1-A_o)} x \frac{100}{100}$$

where:

$A_o$ Initial ash percent, and

$A$ Ash percent at a certain section.

The overall levels of combustion at the end of the visible existed flames are found to be about 98% for all the current runs.

As the exit diameter ratio $D_e/D_i$ (burner exit diameter/burner tube inner diameter) increases from 0.27 to 0.34, 0.5, 0.67 and 1.0: 1) the calculated combustion level of the coal particles at the end of the burner exit is decreases from 90% to 89%, 87%, 84%, and 45% respectively, 2) the average gas temperature at the burner exit decreases from

1455ºC to 1410ºC, 1330ºC, 1250ºC and 1120ºC respectively, 3) the visible flame length –measured from the mixture inlet port to the end of the visible flame- increases from 62 cm to 66, 70, 79, and 94 cm respectively as presented in fig. 6. It is noticed that the flame length increases as the burner exit diameter increases where the structure of the pulverized coal flame is strongly dependent on escaped coal feed rate [23-24], 4) the central reverse flow zone inside the burner tube increases and extends more into the tube.

Also the forward annular exit area increases as shown in fig. 7. The largest reverse flow zone and the biggest annular exit area are found to be for exit diameter ratio 1, consequently the combustible matters have more opportunity to escape through the exit annular area and complete their combustion outside the burner tube. That leads to an increase in the flame length and flame width, consequently higher heat transfer from the flame to the surrounding is expected. The big size of the central reversed flow zone posses a larger torrid entrainment which heat up the fresh coal particles leading to an increase in the devolatilization and reaction rates so, better stable flame is obtained.

At exit diameter ratio 1.0, it is found that 45% of the coal particles flow rate is burnet inside the cyclone burner and the average gas temperature at the burner exit is 1120ºC. While the remaining flow rate of the coal particles (53%) is burnet outside the burner where combustion completed at 94 cm away from the coal feeding port (i.e. flame length). Accordingly, at $D_e/D_i$=1.0 the largest flame is obtained and the maximum radiant heat transfer is expected from this flame to surrounding.

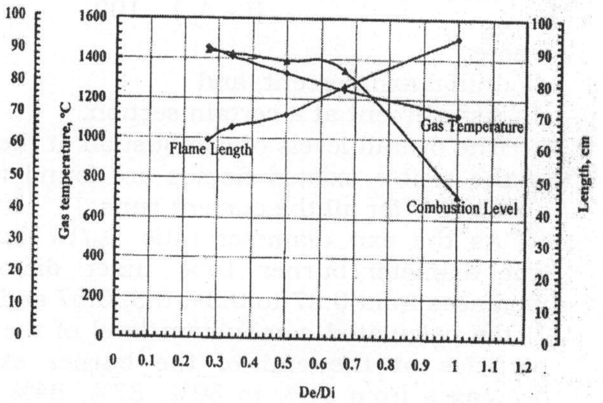


Fig. 6. Combustion level, average gas temperature flame length versus exit diameter ratio ($D_e/D_i$).

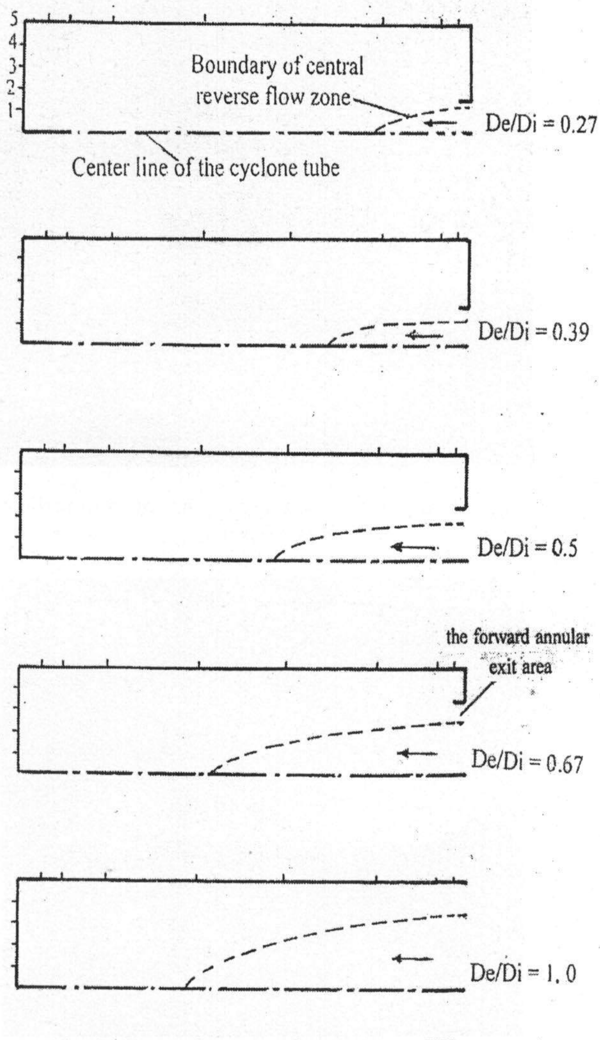


Fig. 7. Central reverse flow zone at different exit diameter ratio ($D_e/D_i$).

## 5. Mobility of the coal-slagging

The formation of mineral deposits on the boiler or furnace walls is one of the major problems resulting from the combustion of coal particles, which results in a reduction in the heat transfer from flame to the wall surface.

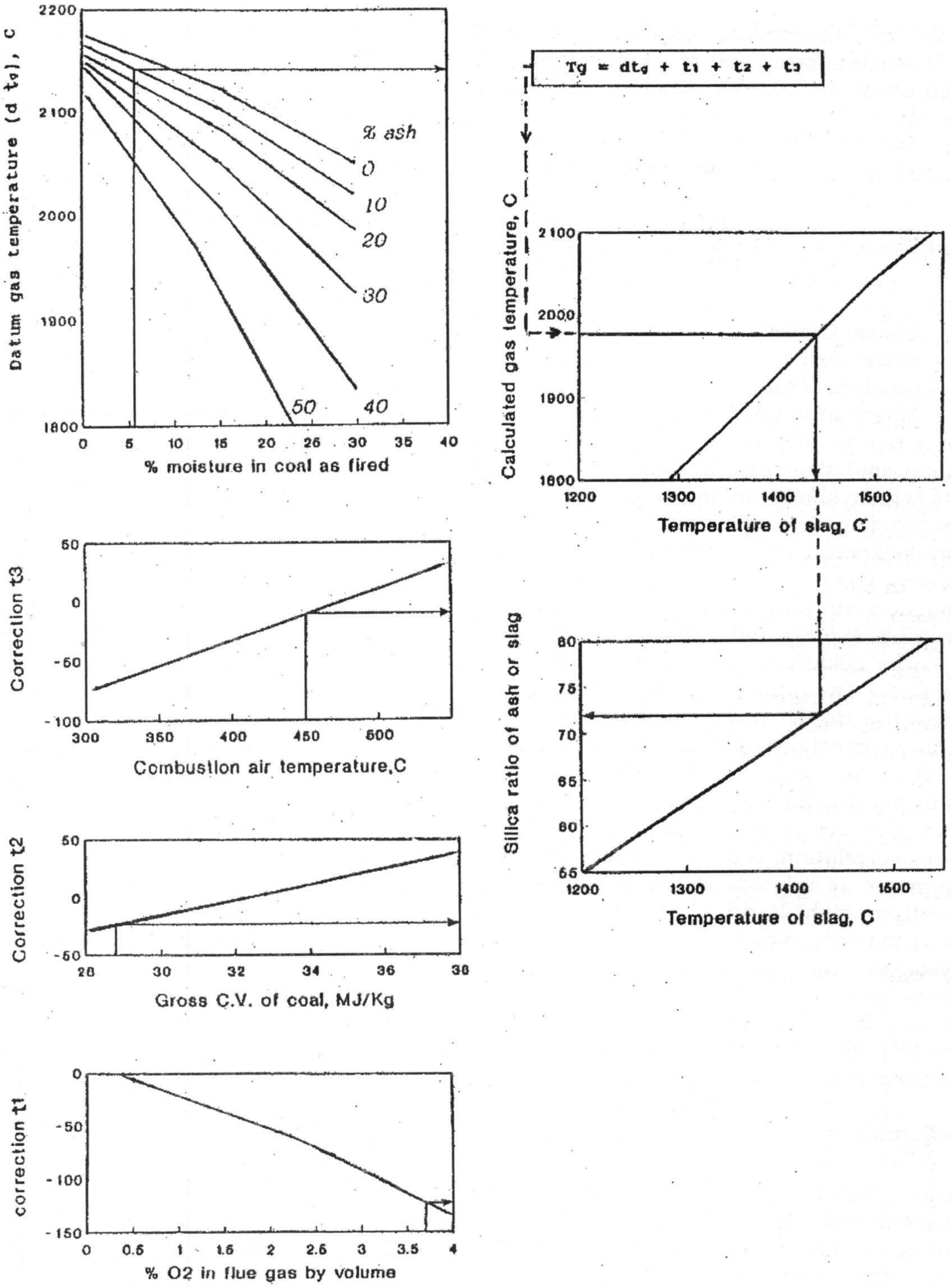


Fig. 8. Determination of silica ratio and coal-slag mobility of Egyptian sub-situminous coal [25].

The sub-bituminous Egyptian Maghara coal particles are found to behave as thermoplastic precursors when it is heated. The critical factor describing the viscosity of the liquid slag is the silica ratio, which is defined as:

$$\text{Silica Ratio} = \frac{S_iO_2}{S_iO_2 + Fe_2O_3 + CaO + MgO}$$

Where:

$S_iO_2$ Silicon Oxide
$Fe_2O_3$ Ferric Oxide
$CaO$ Calcium Oxide
$MgO$ Magnesium Oxide

In order to determine the mobility of the Egyptian coal-slagging, the following steps on charts which shown in fig. 8 [25] is applied. From the four left charts together with the following experimental determined data for the Egyptian coal: ash 10%, moisture 6%, combustion air temperature 450 °C, calorific value 28.8 *MJ/Kg* and oxygen concentration 3.7 %, the calculated gas temperature ($T_g$) is calculated. By obtaining the datum gas temperature $dt_g$ °C from upper left chart and the three corrections factors $t_3$, $t_2$, and $t_1$ then, $T_g = dt_g + t_3 + t_2 + t_1$ . The value of ($T_g$) is substituted in the top right-hand chart to predict the temperature of slag from the shown correlation curve. Then the slag temperature is related by the final graph in the bottom right-hand chart to obtain the silica ratio of the ash. From the above proceedings the silica ratio of Egyptian Maghara coal particles is obtained and its value is 72%. That means the coal-slag is sufficiently mobile to be trapped at the end of the cyclone tube.

## 6. Conclusions

1. The Sub-Bituminous Egyptian coal particles devolatilize when mixed with hot air at 400°C producing hydrogen-rich volatiles and tar which are important for ignition and flame stability. The lighter volatiles are burnet mainly inside the burner tube at 450°C while the heavier volatiles, tar, and char continue their reaction outside the burner tube.
2. The obtainable pulverized coal flame is continuous, stable, smokeless, golden-red colour and extended outside the burner.
3. The overall combustion levels at the end of the obtainable visible flames are found to be about 98% for all the current runs.
4. As the exit diameter ratio $D_e/D_i$ increases from 0.27 to 0.34, 0.5, 0.67 and 1.0: 1) the calculated combustion level of the coal particles at the end of the burner exit is decreases from 90% to 89%, 87%, 84%, and 45% respectively, 2) the average gas temperature at the burner exit decreases from 1455°C to 1410°C, 1330°C, 1250°C, and 1120°C respectively, 3) the flame length increases from 62 cm to 66, 70, 79, and 94 cm respectively, 4) the central reverse flow zone increases and more stable flame is obtained, 5) the opportunity for coal particles to complete their combustion outside the burner increases and larger flame outside the burner is existed.
5. The largest flame is obtained at $D_e/D_i$ = 1.0 and the maximum radiant heat transfer is expected from this flame to surrounding.
6. Slag of the Egyptian Maghara coal-particles is found to be sufficiently mobile and can be trapped at the end of the cyclone tube where its silica ratio is found to be 72 %.

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