FUEL RESEARCH INSTITUTE OF SOUTH AFRICA

TECHNICAL MEMORANDUM NO. 17 OF 1965

SMOKELESS COMBUSTION OF BITUMINOUS COAL IN SMALL APPLIANCES

by

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1. INTRODUCTION:

There exists a widespread opinion that it is impossible to burn bituminous coal smokelessly in small appliances.

It is one of the purposes of this memorandum to refute this notion, although it must be conceded that the results observed in practice seem to support this contention.

The user of a relatively expensive fuel takes it for granted that he also has to use expensive equipment, designed not only to make the best use of the specific fuel, but also constructed to minimise the possibility of faulty handling.

Conversely, when using comparatively inexpensive coal, admittedly not the easiest fuel to burn, it is generally taken for granted that any odd contraption will do. Most of the equipment in use seems to be built with a perverse disregard for the basic tenets of combustion engineering; in addition, the usual designs positively invite mismanagement.

In the following paragraphs, the characteristics of the combustion process, specifically in small furnaces, will be considered in some detail.

2. THE COMBUSTION MECHANISM

In nearly all small hand-fired appliances, the solid fuel rests on a grate through which the combustion air passes upwards, and fresh fuel is added at the top of the bed, which is closed in by a fire box or combustion chamber.

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It is useful to consider the physical aspects of the combustion process in some detail.

With the type of apparatus indicated, one finds, immediately after a fresh charge of coal is added, the following conditions on the grate:

At the bottom, a layer of hot ashes, then a layer of incandescent coal particles, which have largely lost their volatile matter, and, finally, a layer of green coal.

The total thickness of the bed should depend on the particle size of the coal and generally is of the order of 4 inches, or 10 cm. Cold air is drawn in (ideally, through the grate) by the draught produced in the flues and chimney of the apparatus, due to the buoyancy of the hot flue gases. As in the single-storey dwellings prevalent in this country the chimneys are necessarily short, the draught produced is usually low, of the order of 1 to 4 mm. water column.

The cold air is to some extent pre-heated when rising between the grate bars and through the ashes, and more intensively when the incandescent coke or char layer is traversed. Reactions occur between the oxygen of the air and the carbon in the coke, and a considerable portion, or even all the oxygen in the gas stream, is converted into carbon monoxide and carbon dioxide in a proportion which depends on the temperature and on the degree of mixing of the various components of the gas stream. The heat released raises the temperature of the fuel bed and the gas.

The layer of fresh fuel is rapidly heated by conduction from the hot coke layer, by contact with the gas stream, and by radiation (from the flames, if any, the hot gases, and the walls of the fire box).

The volatile matter of the green coal is thus driven off; each particle of the fuel becomes surrounded with a film of combustible gases, which are entrained by the gas stream rising from the grate. This gas stream loses heat by convection and radiation,

partly/...

partly to the fresh fuel but mainly to the fire-box walls or other heat-absorbing surfaces of the appliances.

Combustion of the tar fumes, liberated by the coal, and also of the CO, contained in the gas stream, can only take place if the following conditions are met:

1. The temperature of the gas must exceed the ignition temperature of the combustible components.
2. Sufficient oxygen must be available.
3. The oxygen and combustible components must be thoroughly and intimately mixed.

When these conditions have been met, the actual combustion process takes place at a virtually infinite speed. The time required is thus only dependent on the duration of the mixing process.

Therefore, even when sufficient oxygen is available, combustion will not be complete if the gas temperature drops below the ignition point before complete mixing has been achieved. The tar fumes then condense into myriads of tiny droplets and are the main constituent of the visible smoke resulting from incomplete combustion.

3. THE MIXING PROCESS

As indicated above, this process is the crux of the combustion problem and it is worthwhile to consider this matter in some detail.

Mixing of gases can be brought about by diffusion and by turbulence. The first process is very slow when the gas stream has a width exceeding a few millimeters, as the duration of the process increases with the square of the width. Eck[1)] gives the following example: A jet of 1 mm. in diameter is almost completely dispersed by diffusion in a time of 3 milliseconds. On the above basis, a jet of 1 cm. in diameter requires 0.3 second for dispersal, and for thicker jets the time required for dispersal would be correspondingly longer.

Mixing/...

Mixing by turbulence can be appreciably faster, the speed of mixing being largely dependent on the degree of turbulence, which again depends on the flow pattern.

Now, it may be recalled that two types of fluid flow exist, i.e. laminar or streamline flow and turbulent flow. In the first type, the liquid flows in straight lines or simple curves, closely related to the contours of the channel. In the latter type, the flow lines are of complicated shape and this changes constantly.

The first type of flow is only possible at low velocities, since at higher speeds the flow becomes unstable and the turbulent regime takes over.

The point at which this occurs, and the degree of turbulence thereafter, are characterised by the Reynolds number

$$Re = \frac{W\,b}{\nu}$$

where W is the velocity, b a characteristic linear dimension of the system, and ν the kinematic viscosity of the fluid, all expressed in consistent units. For instance, when fluid flows through a straight circular pipe of diameter d (meters) at velocity W (m/sec), and its viscosity is ν (sec^2/m), streamline flow ceases when $\frac{W\,d}{\nu}$ exceeds a figure of the order of 2400, but for other configurations the critical value of Re is generally different.

Since no turbulence occurs in laminar flow, mixing in this state is still controlled by diffusion and is thus, usually, a slow process.

Insufficient information is available to determine accurately to what degree the speed of mixing is related to the degree of turbulence, or the Reynolds number, but it may be stated, with confidence, that the mixing process is accelerated appreciably when turbulence occurs.

It is thus worthwhile to form some idea of the flow pattern in small appliances.

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4. THE GAS FLOW PATTERN IN SMALL APPLIANCES

This matter is best studied by considering a specific case, and the normal type of domestic water heater (slow-combustion stove), which has a comparatively simple geometry, is a very suitable object for such a study.

The dimensions of such a stove are, roughly, as indicated in Figure 1, which is a slightly schematic version of a large domestic model. The fuel bed is taken to be 100 mm. deep.

It will be assumed that the air enters the fuel bed, after a slight amount of pre-heating in the ashbox, at 27°C or 300°K, and arrives at the top of the fuel bed at a temperature of 927°C or 1200°K.

Such a stove can burn coal at a rate of 3 kg/h, which in practice would require, roughly, 60 kg/h of air.

The chimney will usually produce a draught of between 1 and 4 mm. water column. Since for most appliances a draught of 1 mm. is sufficient, only the lower figure need be considered. When a higher draught is generated, it is necessary to cut down the air rate by means of a damper or throttle. It will be noticed further that a fourfold increase of the draught only doubles the quantity of air drawn in. The maximum velocity to which the air can be accelerated then follows from:

$$\frac{\gamma}{2g} V^2 = p$$

where γ is the density of the air (kg/m^3), V the velocity (m/sec), g the acceleration due to gravity (9.81 m/sec^2), and p the pressure differential available for acceleration (kg/m^2, or what is the same, mm. water column). If the resistance of the fuel bed and the stove is small, p equals the draught, which is then entirely converted into the velocity head.

Since a fourfold expansion in volume of the gas occurs due to the temperature rise (neglecting an increase in volume due to

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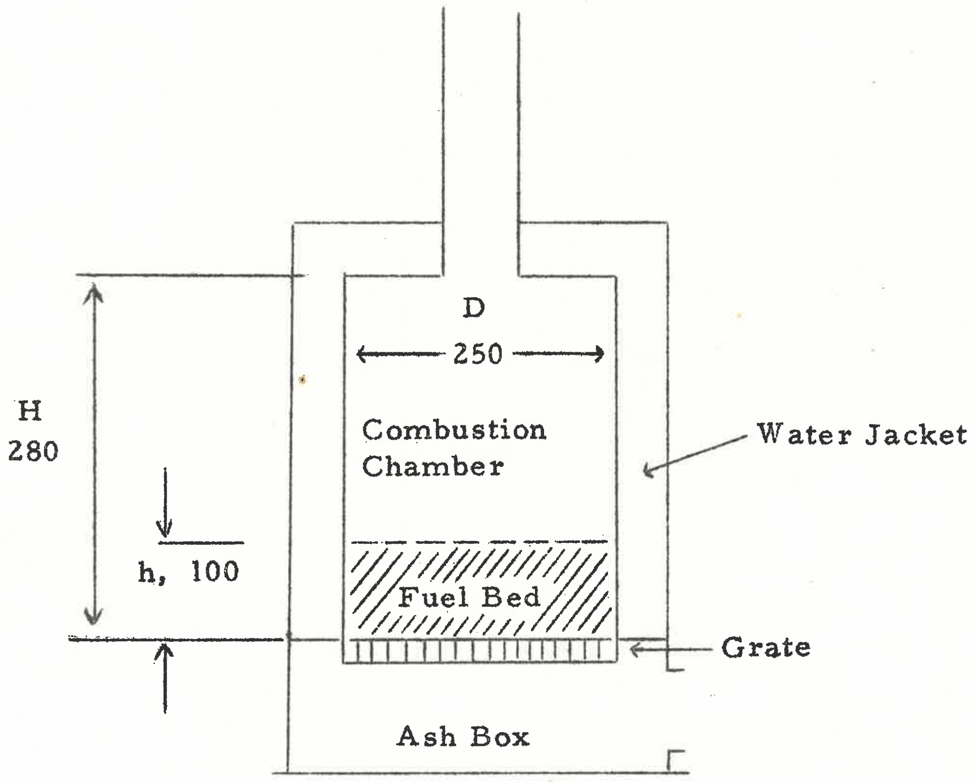
FIGURE 1


D
250
H
280
h, 100
Combustion Chamber
Water Jacket
Fuel Bed
Grate
Ash Box

the formation of CO and H_2O), the highest velocities are likely to occur in the interstices between the coal particles near the top of the fire bed. Conditions here thus determine the maximum velocity that can be attained.

Under the conditions prevailing on the Reef and in Pretoria (air pressure of the order of 625 mm. of mercury), the characteristics of the air (assumed to be dry) are as follows:

Temperature	27°C (300° K)	927°C (1200°K)
Density, γ	0.96 kg/m^3	0.24 kg/m^3
Kinematic Viscosity, ν,	16×10^{-6} m^2/sec	160×10^{-6} m^2/sec.

Thus, if 1 kg/m^2 or 1 mm. W.G. is available to accelerate the air, the maximum velocity which can be attained at 1200°K is found from $\frac{\gamma}{2g} V^2 = 1$, or

$$V = \sqrt{\frac{19.2}{0.24}} = \sqrt{80} = 8.95, \text{ say } 9 \text{ m/sec.}$$

This is the terminal velocity. The entering velocity at the bottom of the fuel bed would be one-quarter of this figure, or 2.75 m/sec.

It will be assumed that the size and the shape of the coal particles are such that this velocity suffices to convey the required amount of air, 60 kg/h, or, at 1200°K, 60 ÷ 0.24 = 250 m^3/hour for the stove considered. (A total area of 77 cm^2 or 16% of the grate area would be required at the above air speed.)

It is, of course, difficult to estimate the average dimensions of each channel, but if one assumes that there are 100 coal particles distributed over the cross section of the stove (which would be about the right number for 1" coal), and that on the average one air channel is associated with each particle, the mean channel area would be 0.77 cm^2, or the mean diameter 1 cm. roughly.

The Reynolds number at the point of entry is, then:

$$Re_1 = \frac{2.5 \times 0.01 \times 10^6}{16} = 1580,$$

and/...

and at the exit:

$$Re_2 = \frac{9 \times 0.01 \times 10^6}{160} = 560.$$

These figures are very low, and even though the irregular nature of the channels may produce some eddies, the turbulence must be expected to be very weak. In addition, one should bear in mind that the whole fuel bed is traversed by the air stream in something less than 0.02 seconds, which probably is too short to fully establish turbulence, even if this should tend to occur.

It should be remembered that a considerable portion of the tar fumes is not liberated in the air channels, but from the exposed surface at the top of the fuel bed.

Here, the gas from the channels loses its velocity over a distance of a few channel diameters, both by entrainment of the surrounding fumes and by contraction due to cooling.

If a uniform upward velocity were attained, a speed of 1.38 m/sec would be obtained at 1200°K and 0.69 m/sec at the top of the combustion chamber (600° K).

The first condition leads to a Reynolds number:

$$Re = \frac{1.38 \times 0.25}{160} \times 10^6 = 2150,$$

which normally would designate laminar flow. Because of the irregular entry of the gas into the combustion chambers, some eddies and slight turbulence may, however, exist, but these effects would be weak and the mixing action poor.

These conclusions agree well with qualitative observations on such a fire: One sees dark and luminous streamers and the flames, which, though not as steady as those of a candle, retain their identity for an appreciable time. Such a picture is certainly not indicative of violent mixing, in which case only an undifferentiated luminous cloud would be seen.

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It should further be mentioned that the gas traverses the combustion chamber at a mean speed of $(1.38 + 0.69) \div 2 = 1.35$ m/sec or in $0.18/1.35 = 0.135$ seconds, a time which is far too short for mixing by diffusion. Moreover, a considerable portion of the gas will be cooled below the ignition temperature (say, 950°K) before leaving the combustion chamber. This means that from this point onwards the chemical reactions are quenched and any mixing which occurs after this stage will be of no avail.

It is, thus, not surprising that attempts to burn high volatile bituminous coal in this type of apparatus (which was in any case not designed for this purpose) do not give satisfactory results. Similar conditions are found to prevail in many coal stoves, kitchen ranges and small vertical boilers.

5. IMPROVING CONDITIONS

The main requirements, obviously, are to provide sufficient time and space to complete mixing at a temperature above the ignition point.

One way of achieving this object would be to provide a large, insulated combustion chamber, so that mixing by diffusion and weak turbulence can complete its course. The apparatus then would become very large, cumbersome and expensive, and a considerable amount of the useful heat would be lost.

Another method is to increase the turbulence artificially. This can be done in two ways:

a) By increasing the speed of the gases in the fuel bed and by letting the issuing streams impinge on baffles of a hot, inert material.

b) By the introduction of air jets at a fairly high velocity.

An application of the first method is illustrated by the underfeed stoker. In this stoker, the coal is fed into a retort from the bottom, air (usually slightly pressurised by a fan) is introduced near the top of the retort, and the incandescent fuel is covered by the hot

ashes/...

ashes. The tar vapours produced at the bottom of the retort not only have a longer way to travel with the air, but are also well-mixed in the tortuous passages through the hot coke and ash layers.

A similar state of affairs exists in the Zavochek water heater, which has been found to operate well in fairly large sizes. Operation on a smaller scale and an adaptation of the principle to stoves and ranges are still to be investigated.

The second method is widely applied in large boilers and industrial furnaces. An investigation of the properties of air jets (as regards penetration, dispersal and mixing effect) was carried out by Rummel(2) and, later, by Rydberg(3) (with special reference to fairly small equipment as central-heating boilers)*. Reference may also be made to the publications of Engdahl et al(5, 6, 7, 8, 9). Though reports of these investigations are not all available, sufficient empirical data exist to demonstrate that this method is most effective.

In medium to large plants, jets working at a pressure of 300 to 600 mm. water column are usually employed.

For small installations these pressures are situated in an awkward range. Some preliminary experiments carried out at the Institute indicate that it may be possible to reduce the pressure considerably so that normally available equipment could be used, for instance a forge blower or a steam-operated air injector for a small vertical boiler, and a vacuum cleaner type fan for a hotel range. Though this involves some expenditure, the cost would be small compared to that of a mechanical stoker and would be recovered rapidly from the savings resulting from the continued use of bituminous coal instead of an expensive smokeless fuel.

6. AFTER-BURNERS

Finally, and for the sake of completeness, it may be mentioned that smoke emission may be completely eliminated by the installation of an after-burner.

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* Thring's(4) down-jets might also be considered to fall in this category.

In most cases the tar vapours and flue gases are quite well-mixed when they leave the appliance, and sufficient oxygen to achieve complete combustion may be present. If the temperature of a portion of the gases is raised sufficiently by means of a pilot flame, the vapours do indeed burn. Apart from the fact that this is a defeatist way out, there are several objections to this procedure. Suitable fuels for the pilot flame are expensive and an appreciable quantity of these is required. In addition, a large quantity of heat is wasted, though, if applied to a stove, this heat could still be used to generate hot water.

7. SUGGESTED MATTER FOR RESEARCH

Based on the foregoing considerations, the following research and development work is proposed:

a) Development of a combustion chamber with magazine and gravity feed, operating on natural draught only. For an apparatus requiring heat at a low rate but over long periods, or continuously, such as water heaters, the prospects are favourable.

b) It should, however, also be investigated whether this mode of operation is also suitable for application where a more intense heat is intermittently required (such as kitchen ranges and space heaters).
The aim should be to produce these appliances at the lowest possible cost, consistent with acceptable quality and performance.

c) Development of equipment with mechanically assisted draught, both for adaptation to existing apparatus and for new constructions. For the latter, the achievement of a high standard of performance and quality should be the main consideration.

d) Development of an after-burner with ignition and reheat derived from the appliance proper.

It may be mentioned here that for small vertical boilers a series of experiments just completed has shown that here smoke

suppression/...

suppression by means of air jets can be satisfactorily solved by fairly simple measures.

It is considered that objectives a) and c) could be attained without undue difficulty. However, the possibility of achieving success with projects b) and d) appears doubtful at this stage.

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PRETORIA,

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