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THE MEASUREMENT OF RADIANT HEAT FLUX IN LARGE BOILER FURNACES—I. PROBLEMS OF ASH DEPOSITION RELATING TO HEAT FLUX

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Abstract — Conditions within a boiler furnace provide an extremely hostile environment for any permanently installed measuring instrument. Design considerations and material selection must take major account of this aspect if the instrument is to have a reasonable life span. Ash is inevitably created during the combustion of coal or oil and will deposit on the furnace walls. Full consideration must be given to the effects of ash if accurate measurements are to be made, and this applies particularly to measurements of heat flux. Substantial errors will occur in indicated heat flux if the instrument does not collect a representative deposit of ash.

NOMENCLATURE

a,	length of instrument measuring cylinder;
e,	emissivity of boiler tube surface;
h_s,	heat-transfer coefficient on boiler tube inside surface;
k_m,	thermal conductivity of instrument measuring cylinder material;
k_t,	thermal conductivity of boiler tube material;
Nu,	Nusselt number;
P,	steam pressure;
Pr,	Prandtl number;
q,	heat flux per unit surface area;
Q,	radial heat flow per unit length of boiler tube;
r_i,	inside radius of boiler tube;
r_o,	outside radius of boiler tube;
Re,	Reynolds number;
T_{bi},	temperature of inner surface of boiler tube;
T_{bo},	temperature of outer surface of boiler tube;
T_f,	equivalent black body flame temperature;
T_i,	temperature of instrument measuring cylinder lower thermocouple;
T_o,	temperature of instrument measuring cylinder upper thermocouple;
T_{mi},	temperature of instrument measuring cylinder base;
T_{mo},	temperature of instrument measuring cylinder surface;
T_s,	saturation temperature;
x,	distance between measuring cylinder thermocouples;
y,	distance between measuring cylinder lower thermocouple and outside surface of boiler tube.

Greek symbol

σ,	Stefan–Boltzmann constant.

1. INTRODUCTION

THERE is a continuing need for measurements of heat flux in boiler furnaces. In power station boilers, the determination of local values of heat flux is required to fulfil three main functions:

1. Heat flux mapping during the commissioning stages of new plant. This will indicate problem areas, if any, for which remedial measures in terms of construction or operation can be incorporated into the current or subsequent plant.
2. Identifying problems associated with heat flux intensity during the operation of existing plant. Appropriate mechanical solutions or improved operational procedures can then be applied.
3. Validation of design methods. Numerous computer programs have been developed for boiler performance calculations. The measured data can be utilised as input for such programs.

In boiler furnaces the environment is particularly severe, with high temperatures and perhaps extremely corrosive combustion products. Thus, careful consideration has to be given to aspects such as material of construction and operating temperature in order that any permamently installed measuring instrument can withstand the conditions throughout its intended design life. The combustion of fossil fuels used in power generation, i.e. pulverised coal and residual oils, inevitably creates ash, which is the residue of incombustible impurities in the fuel. Oil has far less in the way of impurities than has coal, but oil ash corrosion is, if anything, more of a problem than with coal. Ash deposits in oil-fired furnaces are generally quite thin, typically of order 1 mm thick, and could be molten. A thickness of 1 mm does not seem very significant, but it will be shown that in fact it provides considerable resistance to the heat flux into the boiler tubes. The combustible constituents in coal on the other hand lead to the creation of ash in such quantities that it can rapidly build up to deposits many cm thick, which may also become molten. These deposits require regular dislodgement by soot-blowing in order to maintain acceptable boiler performance. All these aspects must be taken fully into account in designing flux measuring devices if accurate and reliable measurements of heat flux are to be obtained.

2. THE PROBLEM OF CORROSION

Fireside tube corrosion is a problem frequently encountered in fossil-fuelled boilers. Both coal and oil ashes contain corrosive constituents, although these vary between the two fuels and between different samples of the same fuel. Much research has been done on the corrosive aspects of fuel ash, e.g. [1–5], and some broad conclusions may be drawn. Those relevant to the current investigation are:

a. The rate of corrosion of boiler materials is very dependent on temperature.
b. Corrosion is greatly accelerated when surface temperatures are sufficiently high that immediately adjacent ash deposits are molten. Ashes melt at widely differing temperatures, depending on their composition.
c. Corrosion is unlikely to be significant at surface temperatures below 600°C. With some oil ashes, corrosion can be severe by 730°C.
d. Whilst typical high strength, oxidation resistant alloys have shown good high temperature corrosion resistance to some fuel ash samples, they have shown poor resistance to others.

There is thus every incentive to try to ensure that the operating temperature of any permanently installed boiler instrument will not be greatly in excess of 600°C. Power stations currently under construction for the CEGB will be operating with maximum evaporator tube surface temperatures approaching 500°C, so that any tube surface mounted flux measuring device preferably should operate with a surface temperature elevation not substantially above 100 K to ensure a reasonable design life (10 000 h).

On the assumption that a modest operating temperature can be achieved, there appears to be little advantage in employing sophisticated high temperature alloys for heat flux meter construction. Ordinary stainless steel grade 321 should offer sufficient corrosion resistance. Nevertheless the design of the device should be such that modest amounts of surface corrosion will not affect its calibration.

3. THERMAL RESISTANCE OF ASH DEPOSITS

The extent to which a layer of ash restricts the heat absorbed by a surface is dependent upon a number of factors. Perhaps the most obvious of these are its thickness, physical structure and chemical composition. These factors in turn are dependent upon other considerations and are also interrelated, as their separate discussion will reveal.

3.1. *Thickness of the ash deposit*

With a permanently installed flux measuring device the intention is to measure the heat flux into the selected region of tube under the prevailing ash coating. As the ash coating is likely to have a high thermal resistance, it is important that the presence of the device does not distort the natural ash deposition processes and thus modify the thickness of the coating and hence the absorbed heat flux.

Ash deposition is a complex phenomenon affected by convection, gravity, burner locations and flame characteristics, and so the thickness cannot be predicted. Thus any heat flux measuring device ideally should conform to the tube shape or produce a minimal discontinuity in order that it will collect a representative thickness of ash.

3.2. *Physical structure of the ash deposit*

Initial deposits on the tube surfaces will be dry, porous and friable in nature, but as the deposit thickens, its overall thermal resistance will increase and its surface temperature will rise rapidly towards the ash melting temperature. Under these conditions, the outer layers will become sticky and start to agglomerate, and finally become molten in regions of highest heat flux. Transmission of heat through the innermost layer will be a combination of several modes, the principal ones being conduction through the solid particles, conduction through the intervening gas pores and radiation across the pores. The relative contributions from each of these modes will be dependent upon such factors as ash composition, particle/pore sizes and ash temperature. In the molten state, heat transmission will be almost entirely by thermal conduction through this now continuous medium, which will have a much lower resistance to heat transfer than the inner dry layer.

3.3. *Chemical composition of the ash*

Fuel oil impurities can vary considerably in chemical composition depending on the sources of these impurities. In some fuel oils, the most significant constituents of the impurities are compounds of sodium and vanadium. These can combine during combustion to form complex compounds with a wide range of relatively low melting temperatures (250–650°C). Thus oil ash seldom has a single sharp melting point, but rather softens and melts over a wide temperature range. Other oils may contain mainly refractory constituents as impurities, such as silica, alumina and iron oxide, in addition to sodium and vanadium, forming ash that will melt over a range of much higher temperatures. Under this circumstance, the layer of dry ash will be thicker under the molten outer layer.

Coal contains mainly refractory materials, particularly silica, as impurities and so coal ash tends to have a higher, more sharply defined melting temperature than does oil ash.

4. SELECTION OF 'TYPICAL' ASH CHARACTERISTICS FOR QUANTITATIVE ANALYSIS

The preceding section has highlighted the problems of attempting any quantitative assessment of ash deposition effects on the output from heat flux measuring devices. The three main characteristics required to determine the effects of an ash deposit on radiation heat flux are its thickness, its effective thermal conductivity and its surface absorptivity (emissivity). Morgan [6] has already investigated the effects of emissivity and so this aspect will receive only brief mention here.

4.1. *Effective thermal conductance*

Several investigators have made measurements of the effective thermal conductance of solid fuel ash deposits removed from boiler surfaces. Golovin [7] made measurements on samples of anthracite ash and quotes values in a range 0.012–0.023 W m K^{-1}, which are considerably below that of air. Prasolov and Vainshenker [8] measured thermal conductivities of a wide variety of ashes including numerous bituminous coals. Their values were in the range 0.04–0.26 W m K^{-1}. The most comprehensive investigation was by Boow and Goard [9], who examined the effective thermal conductance of thirty-four inorganic combustion deposits from Australian coals. The main conclusions from their investigations are as follows:

(i) The chemical composition of the unsintered ash is of secondary importance compared with its thermal history of formation in determining its thermal conductance. Ash samples with widely differing silica content taken from a particular boiler had very similar thermal conductances. Laboratory produced ashes of similar chemical composition to the boiler samples had very different thermal conductances to the boiler samples.

(ii) Effective thermal conductance is considerably influenced by particle size. Deposits of larger median particle size had a higher conductance. Typically, a median size of 300 μ had a thermal conductance some 75% above that for an ash of 100 μ median size.

(iii) The thermal conductance increases with temperature, and once sintering begins, this increase is much more rapid such that in the completely fused state, the thermal conductance can be an order of magnitude higher than at the start of sintering. Figure 1 is a reproduction of measurements of effective thermal conductance of several Australian power station coals. Chemical composition does of course affect the sintering temperature.

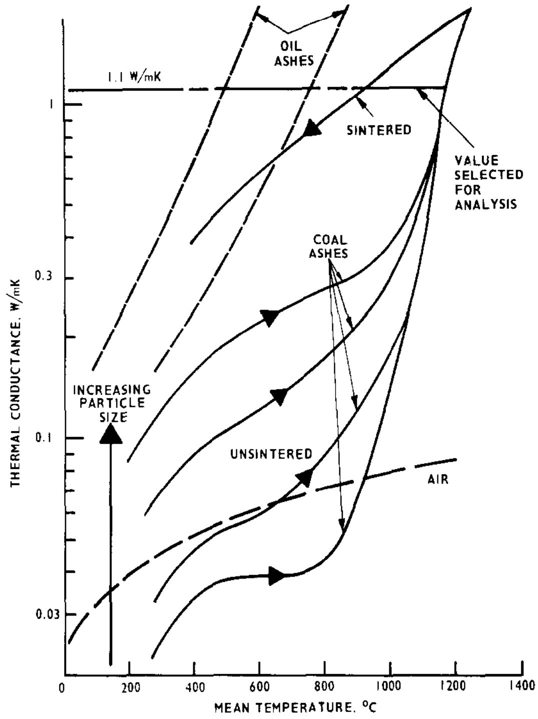


FIG. 1. The effective thermal conductance of several samples of coal ash deposits from Australian coals (data from Boow and Goard [9]) and of two samples of oil ash (Ivanov and Chudnovskaya [11]).

The insensitivity of thermal conductance to chemical composition, before the onset of sintering, is explained by the fact that in a porous medium, thermal conduction through the solid is only one of several modes of heat transmission. In an investigation of thermal conductance in a high temperature refractory of 70% porosity, for instance, Young *et al.* [10] found that conductivity through the solid accounted for only 22% of the total conductance. Thus, substantial changes in particle thermal conductivity can have a relatively small influence on the effective thermal conductance. Differences in particle size are likely to be a much greater influence, and account for most of the variation between the samples shown in Fig. 1 where again the lowest median particle size samples had thermal conductances of the same order as, or less than, that of air at the same temperatures. Boow and Goard say that for these thermal conductances to be as low as observed, the voids in the direction of heat flow must be small enough to allow free molecular flow (or Knüdsen conduction) to predominate. This process, which occurs at all boundaries between a gas and a solid, is less efficient than the bulk collision mechanism and so accounts for these very low values.

The effective thermal conductance of oil ash deposits has been measured by Ivanov and Chudnovskaya [11] using a special sampling unit which was inserted into the boiler to collect deposits over a range of metal surface temperatures. They obtained values for effective thermal conductance rather higher than those measured for solid fuel ashes, and put this down to the fact that oil ash deposits are of polycrystal formation with fairly large original particles which have good contact with one another. Two examples from their measurements are included in Fig. 1.

In estimating an effective thermal conductance for ash deposits in a modern highly-rated boiler with fluxes of 600–700 kW m^{-2}, it has to be borne in mind that even with thin oil ash deposits, the outer surface of the ash will almost certainly be molten, although immediately adjacent to the tube surface, the ash may be unsintered. By selecting an effective conductance appropriate to a fully fused state, it was considered that the subsequent thermal analysis would probably provide a conservative estimate of the errors produced by unrepresentative ash deposits. Accordingly a value of 1.1 W m^{-1} K^{-1} was chosen. This is appropriate to oil ash and coal ash temperatures of approximately 700°C and 1200°C respectively, which are the order of mean ash temperatures that would be anticipated at the highest fluxes currently encountered.

4.2. *Ash thickness and emissivity*

As mentioned already oil ash deposits in boilers are typically of order 1 mm thick and so this thickness was chosen as a datum from which to assess the effects of an unrepresentative thickness. In the case of coal ash deposits, conditions can vary from a thin deposit immediately after soot-blowing, to a thick deposit with a 'curtain' of molten slag flowing down the furnace wall. This latter condition involves entirely different considerations in determining its effects on heat flux measurement, for which theoretical analysis is inappropriate. The effects of heavy slagging will therefore be discussed later.

Morgan [6] has measured the emissivity of both oil and coal ash under conditions of heating and cooling and his results are shown in Fig. 2. Each sample was heated until it sintered and was then cooled. In both cases the emissivity rose during sintering, but in the case of oil ash, the variation in emissivity over the entire temperature range was no more than 10%. The absorbed heat flux is directly proportional to the emissivity and so the magnitude of likely errors due to differences in emissivity through temperature elevation of the flux meter will be of similar order. Preliminary estimates of the effects of ash thermal resistance showed them to be considerably greater than those of ash emissivity and so a constant emissivity of unity has been assumed in the following analysis for simplicity.

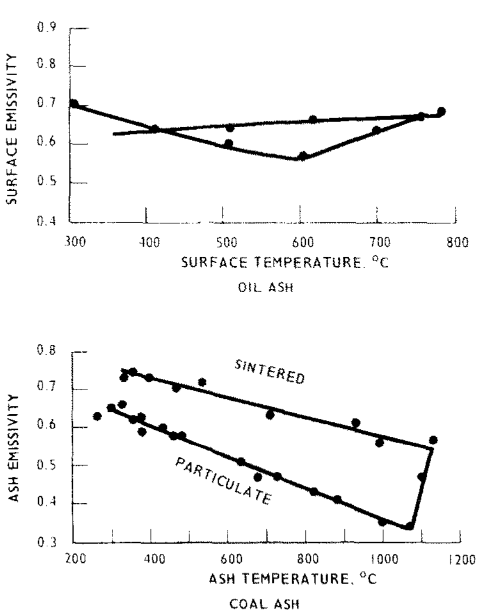


FIG. 2. Measurements of oil and coal ash emissivities under conditions of heating and cooling (Morgan [6]).

5. THE SENSITIVITY OF FLUX MEASURING DEVICES TO ASH THERMAL RESISTANCE

The sensitivity analysis has been carried out on a concept of heat flux meter which utilises probably the most widely employed basic method of measurement.

The method makes use of the temperature gradient generated along a cylinder of known thermal conductivity when heat is applied to one end whilst the other end is connected to some form of heat sink. The temperature gradient is measured by thermocouples at a known spacing along the cylinder. For boiler heat flux measuring devices the heat sink is usually the boiler tube. To ensure that the heat flow in the measuring cylinder is essentially axial, it must be surrounded by a thermal guard that exhibits a temperature gradient similar to that along the measuring cylinder. The thermal guard for a surface mounted flux measuring device will be some form of concentric cylinder as shown diagrammatically in Fig. 3. Alternatively, the measuring cylinder might be incorporated into the boiler tube wall, which itself then acts as the guard. This latter concept, also illustrated in Fig. 3, is ideal since it provides no external geometric discontinuity and so is very likely to collect a representative thickness of ash. Additional wall thickness may be obtained to incorporate the measuring cylinder by locally deforming the tube by cranking or dimpling and then restoring the original external profile by weld

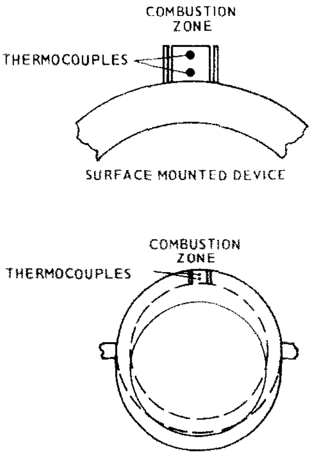


FIG. 3. The two types of boiler tube heat flux measuring device.

deposition and machining smooth. The guarded concept has the advantage that its calibration is unaffected by modest amounts of surface corrosion. An unguarded device has not been considered in this investigation since it may be shown that the calibration of such a device is significantly altered both by corrosion and by the presence of ash.

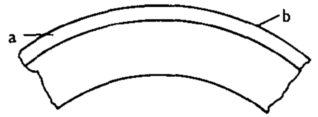
The effects of an ash deposit have been examined using simple finite element computer models of the devices, using the heat conduction computer program FLHE [12]. Using the datum condition of a 1 mm thick layer of ash over the boiler surfaces, the effects were examined of having a 2 mm thick layer on the surface-mounted device, as observations have indicated that surface projections tend to accumulate thicker coatings of ash than do the undisturbed boiler tubes. Additionally, the effects were examined on both types of device of different receiving surface temperature elevations. Fully effective guarding was assumed, although it should be pointed out that with a surface mounted device this could be impossible to achieve in practice since it requires perfect temperature matching between guard and measuring cylinder. Nevertheless, the arguments will apply to the same extent.

The analysis showed that a surface mounted device with a 2 mm coating of ash would absorb 28% less heat than it would with a 1 mm coating. If additionally, the device operates with a surface temperature elevation of 50 K above the adjacent boiler surface, the reduction in heat absorbed is 30%, and with a temperature elevation of 180 K, 39%. For a tube wall inserted device, carrying a 1 mm representative ash coating, a surface temperature elevation of 50 K produces a reduction in heat absorbed of 4%, whilst for a 180 K temperature elevation, the reduction is 28%.

The results of this investigation have been summarised in Table 1. Both types of device are assumed to give the correct indication of heat flux when operating at tube surface temperature and coated with a 1 mm thickness of ash. The final column shows their behaviour in the clean surface condition. In practice, heat fluxes do not reduce to the extent indicated in the table between the clean and ash-coated conditions since the flame temperature would increase as ash deposited over the surfaces. The calibration of a surface mounted device will change between the clean and ash-coated conditions if the ash increases its radiation absorption area by an amount different to that of a plain boiler tube, although this is likely to be a small effect.

In regions of lower flux, the ash deposit could remain unsintered. In this situation, its effective thermal conductance would be much lower, perhaps by a factor of ten, and the errors given in the table would be much larger. As an example, an effective thermal conductance reduced by a factor of five would increase the error through having a non-representative ash deposit on a surface-mounted device from 28 to 60%.

Finally in this section, in order to assist in the assimilation of the different factors applicable to each type of heat flux measuring concept, Fig. 4 has been included, which summarises the shortcomings of each when operating under a coating of ash. It is clear from this investigation that considerations of ash thickness and device surface temperature must form an integral part of the design procedure for any flux measuring device.

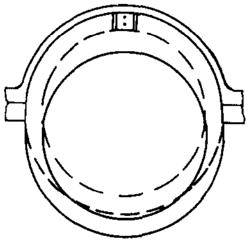


1. PLAIN TUBE

In the presence of ash, the heat flux into the tube will be

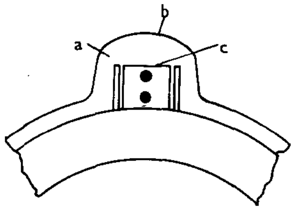
(a) reduced due to the ash

(b) increased due to the increase in radiation absorption area



2. THICKENED TUBE

In the presence of ash, the heat flux into the device will differ from that into the tube through having an elevated surface temperature



3. SURFACE MOUNTED DEVICE

In the presence of ash, the heat flux into the device will differ from that into the tube through having

(a) an unrepresentative ash deposit thickness

(b) an unrepresentative increase in radiation absorption area

(c) an elevated surface temperature

FIG. 4. Heat flux metering concepts and their shortcomings when coated with ash.

6. THE SITUATION WITH HEAVY SLAGGING

In coal-fired furnaces the non-combustible constituents in the fuel are in far greater preponderance than for oil. Because of this, and owing also to their much higher melting temperature, coal ash deposits will accumulate to much greater thicknesses on the boiler tube surfaces. These deposits are removed periodically by a soot-blowing system. The flux absorbed by a given region of boiler tube wall fluctuates as the deposits build up and either fall away or are removed. It therefore follows that the fluxes will be both temporally and spatially variable so that individual measurements made with tube mounted,

Table 1. Likely errors of two types of boiler tube heat flux measuring device as a result of ash deposition

	Normalised values (expressed as percentages) of heat flux into the boiler tube									
	1 mm ash deposit on device and tubes		2 mm ash on device 1 mm ash on tubes		2 mm ash on device 1 mm ash on tubes Device temperature elevation 50 K		2 mm ash on device 1 mm ash on tubes Device temperature elevation 180 K		Clean surfaces (No ash)	
	Actual	Indicated	Actual	Indicated	Actual	Indicated	Actual	Indicated	Actual	Indicated
Surface mounted device	100	100	100	72	100	70	100	61	120	≃ 120
Tube wall inserted device	100	100	100	(100)*	100	96†	100	72†	120	120

*Tube wall inserted device will always carry a representative ash thickness.

†Applies for uniform coating on tube and device.

instruments in all probability will not be very representative of average conditions. This must be borne in mind when interpreting the results obtained from this type of instrument.

Whilst it is probable that once ash deposit thicknesses exceed a few mm, the profile of the instrument beneath it is unimportant, it is essential that the initial thinner coatings are deposited alike on instrument and on undisturbed tube. As has been shown, the first few mm of ash, be it coal or oil, have a significant effect on the flux absorbed by the tube.

7. INCIDENT RADIATION FROM THE FLAMES

It became evident during this investigation that in addition to permanently installed absorbed flux measuring instruments, there was a need to be able to measure local values of the incident radiation from the flames. Such measurements would allow the flame radiation intensities to be determined free from the variable attenuation effects of the ash deposits. Furthermore, with both types of measurement available, local values of the ash thermal resistance could be deduced at any time during boiler operation. An incident radiation flux measuring instrument would have to have a known, high absorptivity, operate with a low receiving surface temperature and would also have to be removable to allow the sensor surface to be kept free from ash. Thus a portable, direct indicating type of instrument appeared to offer the best solution to this problem.

8. CONCLUSIONS

There is every incentive to ensure that the operating temperature of any permanently installed boiler heat flux measuring device is not substantially above 600°C, which is little more than 100 K above the maximum evaporator tube temperature in regions of highest flux, in order that the device has a reasonable operating life and accuracy.

The device must be of such a shape that it will collect an ash deposit of similar thickness to that on adjacent tube surfaces, otherwise substantial errors in heat flux measurement will result.

The design of the device should be such that its calibration is unaffected by modest amounts of surface corrosion.

There is a requirement for a portable device for measuring incident radiation heat flux from furnace flames, free from the variable attenuation effects of ash deposition.

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LA MESURE DE FLUX THERMIQUE RAYONNE DANS LES GRANDS FOYERS DE CHAUDIERE—1. PROBLEMES DUS AU DEPOT DE SUIE

Résumé—Les conditions dans lesquelles fonctionne un foyer de chaudière correspondent à un environnement extrêmement hostile pour n'importe quel instrument installé de façon permanente. La conception et la sélection des matériaux doivent tenir compte de cela si l'instrument doit avoir une durée de vie raisonable. La suie est inévitablement créée pendant la combustion du charbon ou de l'huile et elle se dépose sur les parois. Il faut porter une attention particulière aux effets de la suie si l'on veut faire des mesures précises, en particulier de flux thermique. Des erreurs importantes peuvent être commises dans la mesure du flux si l'instrument ne collecte pas un dépot représentatif de suie.

DIE MESSUNG DES STRAHLUNGSWÄRMESTROMS IN GROSSEN VERDAMPFER-HEIZFLÄCHEN—I. PROBLEME DER ASCHENABLAGERUNG IM HINBLICK AUF DEN WÄRMESTROM

Zusammenfassung—Die Verhältnisse einer Verdampfer-Heizfläche stellen eine extrem feindliche Umgebung für jedes dauerhaft installierte Meßinstrument dar. Gesichtspunkte der Konstruktion und Materialauswahl müssen diesen Aspekt mit einbeziehen, falls das Meßinstrument eine akzeptable Lebensdauer haben soll. Bei der Verbrennung von Kohle oder Öl entsteht unvermeidlich Asche, die sich auf der Heizfläche niederschlägt. Wenn genaue Messungen durchgeführt werden sollen, muß der Einfluß der Asche voll berücksichtigt werden, dies ganz besonders bei Wärmestrom-Messungen. Der angezeigte Wärmestrom ist mit wesentlichen Fehlern behaftet, falls sich am Meßinstrument nicht eine repräsentative Aschenauflage bildet.

ИЗМЕРЕНИЕ ЛУЧИСТОГО ТЕПЛОВОГО ПОТОКА В ТОПКАХ БОЛЬШИХ ПАРОВЫХ КОТЛОВ — 1. ВЛИЯНИЕ ОТЛОЖЕНИЙ ЗОЛЫ НА ИЗМЕРЯЕМУЮ ВЕЛИЧИНУ ТЕПЛОВОГО ПОТОКА

Аннотация — Условия внутри топок паровых котлов являются весьма неблагоприятными для стационарных измерительных приборов. Этот фактов необходимо учитывать при конструировании прибора и выборе материалов для его изготовления, если предполагается длительный срок эксплуатации прибора. При сгорании угля или нефти образуется зола, откладывающаяся на стенках топки. Необходимо тщательно исследовать влияние отложения золы на точность показаний прибора, особенно при измерении величины теплового потока. При недостаточной толщине слоя золы на поверхности прибора в регистрируемых значениях величины теплового потока могут иметь место значительные ошибки.