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Measurements on a Blast-Furnace-Gas and Oil-Fired Combustion Chamber of a 17.25-MWe Closed-Cycle Gas Turbine Plant

K. BAMMERT

Director,
Institute for Turbomachinery and Gasdynamics,
Technical University of Hannover,
Hannover, West Germany

H. REHWINKEL

Scientific Collaborator,
Institute for Turbomachinery and
Gasdynamics, Technical University of Hannover,
Hannover, West Germany

The paper discusses the present stage of development of combustion chambers for fossil-fired closed-cycle gas turbines, describing West Germany's "Gelsenkirchen" plant which can be operated with blast-furnace gas and fuel oil with any desired ratio of gas to oil. The output data and the efficiency of this plant are illustrated by test results. In the development and construction of fossil-fired closed-cycle gas turbine plants, the gas heater presents the greatest difficulties and is the most expensive part of the plant. Therefore, very detailed measurements were taken to determine the total heat absorption in the combustion chamber and its local distribution over the length of the chamber. The results obtained are compared with previous measurements at a smaller plant, the mine-gas and pulverized-coal fired "Haus Aden" plant.

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Measurements on a Blast-Furnace-Gas and Oil-Fired Combustion Chamber of a 17.25-MWe Closed-Cycle Gas Turbine Plant

K. BAMMERT H. REHWINKEL

INTRODUCTION

The development of the fossil-fired closed-cycle gas turbine is largely dependent on the development and construction of suitable gas heaters for transferring the fuel heat to the working medium of the closed cycle. Of all components of the cycle, the gas heater presents the greatest difficulties in layout and operation and constitutes, still in our days, the most important cost factor. The high temperatures of the working medium in gas heaters, in conjunction with the low heat-transfer coefficients on the inner side of the tube, necessitates particularly large radiation surfaces in the combustion chamber.

As the tube wall temperature in the combustion chamber is in the range from 600 to 800 C, you have to use expensive austenitic materials. For economical reasons, it is not admissible to design the tube lining in general for a temperature which is only calculated by adding a constant value to the turbine inlet temperature.

As the working medium in the heater is not subject to any changes in its state of aggregation, each shifting of the heat transfer causes a corresponding change in the temperatures of the working fluid and the tube walls. Therefore, for the layout of the tube lining of the combustion chamber, it is necessary to know, as exactly as possible, not only the total heat absorption in the combustion chamber, but also its local distribution over the length of the chamber.

The calculations for the combustion chamber of the first pulverized-coal-fired air heater of the "Ravensburg" closed-cycle gas turbine plant were based on the experiences gained in steam boiler construction. The available irradiation curves originated from measurements on the burned gas side of a slag furnace boiler (1).[1] The assumptions for the layout were checked later on by tests on this plant (2).

[1] Underlined numbers in parentheses designate References at end of paper.

The "Ravensburg" plant with its maximum output of 2.3 MWe was at the lower limit for pulverized coal firing. It was the pattern for the similarly pulverized coal-fired, "Coburg" gas turbine plant (6.6 MWe) and "Oberhausen" plant (13.75 MWe). Contrary to the other plants, the "Oberhausen" plant is equipped with two combustion chambers. The problems, which had to be solved in developing the "Ravensburg" construction-principle for higher outputs, and the design solutions adopted in this connection, are described in references (2) and (3).

The "Haus Aden" plant (6.37 MWe), the air heater of which is an improvement of the type used at the "Coburg" plant, is fired with a mixture of mine gas and pulverized coal. In the combustion chamber of this air heater, extensive measurements were taken. The aim was to determine the local and mean heat flux densities in the combustion chamber when firing with coal, gas, and coal-gas mixtures. The measurements taken at the "Haus Aden" gas turbine plant are described in detail in several papers issued previously (4-6).

The latest achievement in this development is the "Gelsenkirchen" plant, which went into operation in 1968 at a Western German steel mill. It is the largest closed-cycle gas turbine plant in operation, having an output at terminals of 17.25 MWe. The first-rank fuel is the blast-furnace gas of the steel mill. To compensate the variations in gas supply, there is added light fuel oil.

In order to extend the existing informations and data about the distribution of the heat absorption in combustion chambers of gas heaters and to cover a wide fuel range and higher outputs, again extensive measurements in the combustion chamber were taken at the "Gelsenkirchen" plant. In connection with these investigations, some efficiency tests of the whole plant were made. The performance and the results of these measurements, in comparison with those previously taken at the "Haus Aden" plant, are treated in this paper.

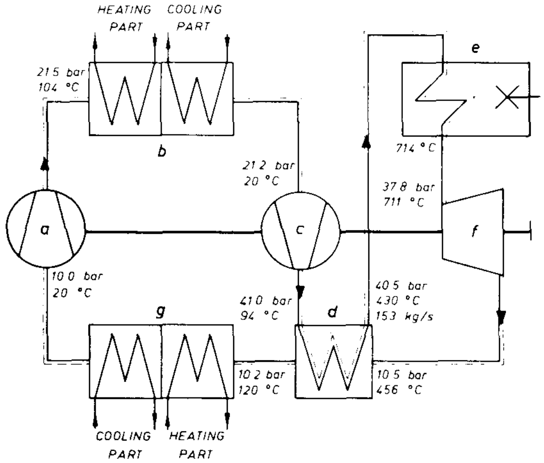
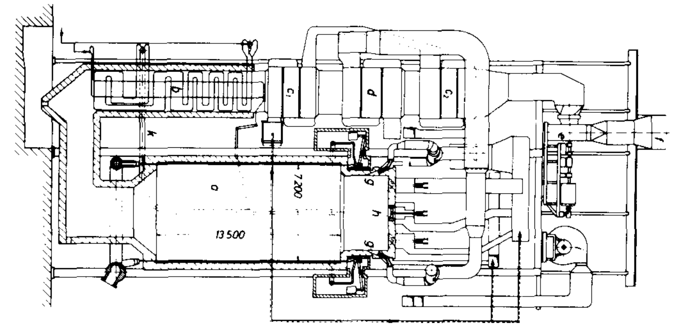


Fig.1 Schematic diagram of the "Gelsenkirchen" gas turbine plant



a	combustion chamber	f	stack
b	convection part	g	blast-furnace-gas burner
c_1, c_2	combustion-air preheater	h	oil burner
d	blast-furnace-gas preheater	i	forced-draft fan
e	induced-draught fan	k	connection pipes

Dimensions in mm

Fig.2 "Gelsenkirchen" air heater

DESCRIPTION OF THE "GELSENKIRCHEN" PLANT

A schematic diagram of the plant is shown in Fig.1. The air passes the low-pressure compressor, a, is cooled in the intercooler, b, and brought to the maximum cycle pressure in the high-pressure compressor, c. Preheating in the heat exchanger, d, is followed by the final heating in the air heater, e. In the turbine, f, the working medium is expanded; in the following heat exchanger and in the precooler, g, it is brought again to its initial temperature. At the design point, the pressure at the turbine inlet is 37.8 bar,[2] the turbine inlet temperature amounts to 711 C, the temperature at the compressor inlets is 20 C, and the mass flow at the turbine inlet is 153 kg/sec. The expansion ratio of the turbine is 3.6. With a temperature difference of 26 C on the hot side of the heat exchanger, the air temperature at the heater inlet is 430 C.

Normally the air enters the precooler at 120 C and the intercooler at 104 C. These high temperatures allow more than 60 percent of the waste heat to be utilized for heating purposes, without affecting the net efficiency of the plant. Therefore, the coolers are divided into a cooling part and a heating part on the water side. The output at the coupling of the machine set is transmitted to the alternator by a gearing.

In Fig.2, the air heater is shown. It is mounted out of doors in front of the machine house, on the extended axis of the machine set. The roof-fired combustion chamber, a, is an octagonal radiation chamber with a width over flats of 7.2 m and a tube length under radiation of 13.5 m. On the burned-gas side follow the convection part, b, and the divided combustion air preheater, c_1 and c_2, with the blast-furnace-gas preheater, d, between c_1 and c_2. The induced draught fan, e, forces the flue gas through the steel stack, f, mounted on the air heater.

The combustion chamber is equipped with eight blast-furnace gas burners, g, in the walls of the ignition muffle and five oil burners, h, in the roof of the ignition muffle. During normal operation, 90 percent of the heat is produced with blast-furnace gas and 10 percent with light fuel oil. The fuel oil is added for the carburization of the flame and thus for improving the heat transfer through radiation in the combustion chamber. Depending on the operating requirements and the supply of gas, the air heater can be fired with any desired ratio of gas to oil, with the full output obtained with either fuel alone or with any mixture of the two fuels.

The combustion air is drawn in by the forced-draft fan, i, heated by the burned gas in the two-stage air preheater to about 450 C, and then led to the gas-burner and oil-burner groups in separate streams. The temperature to which the blast-furnace gas is raised in the flue-gas fired preheater is about 300 C.

The cycle air leaves the heat exchanger at 430 C, passes the convection part of the heater in the second pass, first in a cross-counterflow, and finally in a cross parallel flow relative to the flue-gas stream, is collected at about 570 C after leaving the convection part, and then admitted through two connection pipes, k, to the combustion chamber inlet header. The air passes through the

[2] 1 bar = 14.504 psi.

straight tubes in parallel to the flame and is heated by radiation to the final temperature of 714 C. The heat to be transferred to the cycle air amounts to 41.5 gcal/hr[3] at full load in the design case.

The oil burners are of the pressure atomizer type. The oil feed is controlled by the pressure in the return pass. The blast-furnace gas burners are of the parallel flow type. The gas pressure at the burner inlets is about 200 mm water gage.

ARRANGEMENT OF THE MEASURING POINTS

During the efficiency tests on the plant, the quantities needed for the calculation of the plant efficiency (output at alternator terminals, fuel consumption), as well as the data of the cycle air (pressure and temperature) upstream and downstream of each component were measured. Furthermore, the losses of the machine set were ascertained directly by measuring the heat transferred to the cooling water and the lube oil.

An important aim of the investigations on the air heater was the determination of the total heat absorption in the combustion chamber as a function of the load and the firing conditions. For establishing an accurate heat balance for the combustion chamber, particularly the following data were measured: the mass flows of the cycle air, the blast-furnace gas, the fuel oil, and the combustion air, the calorific values of the blast-furnace gas and the fuel oil, the sensible heat of the blast-furnace gas and the combustion air, and the heat content of the burned gas after leaving the combustion chamber.

The heat absorbed by the cycle air was ascertained directly from the mass flow and the temperature difference between the inlet header and the outlet header of the combustion chamber. It differs from the transferred heat by the amount of the radiation loss.

The temperatures in the cycle and in the air heater were measured with thermocouples. The values were recorded by an automatic data acquisition plant at intervals of 3 min., together with the pressures on the burned-gas side of the air heater. By means of this installation, it was possible to measure all important quantities in the cycle and at the air heater at the same time and still keep the number of staff for the tests within tolerable limits.

The pressures of the cycle air were measured with precision gages, and the pressure drops with differential pressure gages in the usual manner.

For determining the local irradiation in the combustion chamber, two special measuring tubes were substituted for two normal heating tubes. In each of the measuring tubes, 14 miniature thermocouples were mounted, which enabled the temperature increase of the cycle air and, thus, also its enthalpy increase as a function of the length of the combustion chamber to be measured. Fig.3 shows a measuring point. The miniature thermocouple, a, is held in the tube axis by two guides, b. It is contained in a polished radiation protection tube, c, of stainless steel — open in flow direction — which has the purpose of preventing incorrect temperature indication due to radiation from the hot tube wall. By means of two holders, d, the radiation protection tube is fixed to the measuring tube, e. The thermocouple is brought out by a pressure-tight nipple, f. By the threaded union, g, an air-cooled guide tube, h, is connected to the measuring tube. An expansion bend of the protective tube in the combustion chamber ensures that the measuring tube can move freely in the direction of its longitudinal axis relative to the brickwork. The purpose of the protective tube is to cool the thermocouple with compressed air and to protect it against corrosion in the combustion chamber and at the point where it passes through the brickwork.

At their lower end, the two measuring tubes were not connected to the outlet header but laterally brought out through the brickwork. After recooling, the air was re-fed into the cycle between the LP and HP compressors. With a throttle valve, the mass flow through the measuring tubes could be adjusted so that the temperature at the outlet of the measuring tubes was equal to the mean temperature of all tubes (measured in the pipe to the turbine).

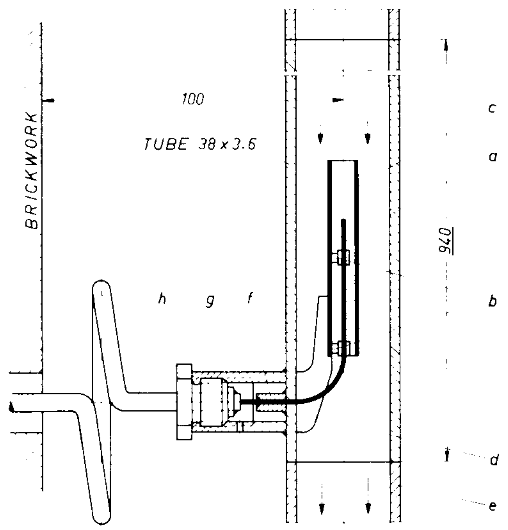
Besides, the material, the dimensions, and the method of fixing the measuring tubes in the tube banks were correspondent to the conditions at the normal combustion chamber tubes so that also the geometrical conditions for irradiation were equal to those of a normal tube.

The measurements taken a few years ago in the combustion chamber of the "Haus Aden" plant were very similar to those at the "Gelsenkirchen" plant regarding the problems examined and the methods of realization. The measuring tubes described here were used at "Haus Aden" with basically the same design. These measurements at the "Haus Aden" gas turbine plant are described in detail in various papers (4-6), so that it is not necessary to discuss any further details here.

EFFICIENCY DATA OF THE "GELSENKIRCHEN" PLANT

The efficiency at terminals was determined

[3] 1 gcal = 10^6 kcal = $3.968 \cdot 10^6$ Btu.



a miniature thermocouple
b guide
c radiation protection tube
d holder
e measuring tube
f nipple
g threaded union
h protective tube

Dimensions in mm

Fig.3 Measuring point within the measuring tube

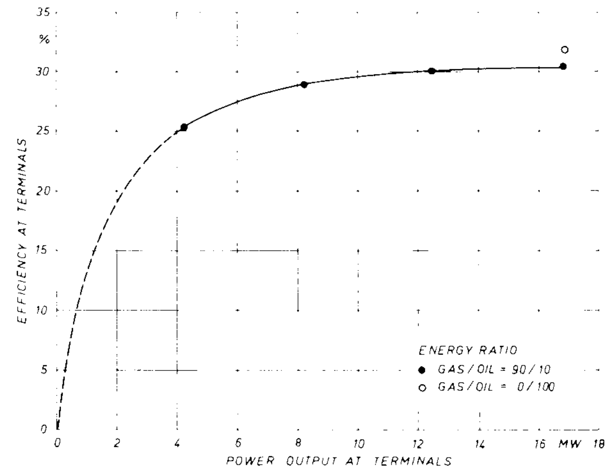


Fig.4 Efficiency at terminals with mixed-fuel and oil firing

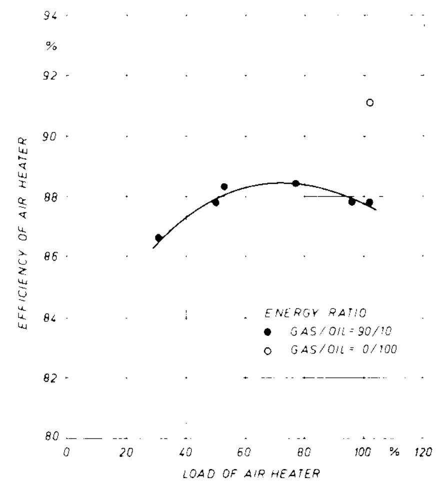


Fig.5 Air heater efficiency with mixed-fuel and oil firing

at an air temperature at the compressor inlet of 20 C and a turbine inlet temperature of 711 C, according to the cycle diagram in Fig.1. The other parameters are adjusted automatically when the alternator runs with synchronous speed, and the mass flow in the cycle corresponds to the desired output.

Fig.4 shows the measured efficiencies of the plant plotted against the output at terminals. The efficiency is defined as the ratio of the output at the alternator terminals to the fuel heat fed into the heater. In Fig.4, the curve shows the efficiency when 90 percent of the fuel is blast-furnace gas and 10 percent oil. Attention is invited to the flatness of the curve down to less than half the load. A remarkable decrease in efficiency does not occur until the load decreases below one quarter. This favorable behavior at partial loads is due to the pressure level control, which ensures that the temperatures and volumes upstream and downstream of the components of the plant remain almost constant also at part load. Fig.4 shows also, as a single point, the efficiency with pure oil firing at full load. The difference in comparison with the curve is exclusively due to the fact that with oil firing the efficiency of the heater is higher.

The optimum efficiency of the plant when firing with 90 percent blast-furnace gas and 10 percent oil is 30.4 percent, and when firing with 100 percent fuel oil, it is 31.7 percent. The corresponding efficiencies of the air heater are 87.8 and 91.1 percent, respectively.

The curve of the air heater efficiency as a function of the load is shown in Fig.5. The efficiency is defined as the ratio of the heat transferred to the cycle air to the fuel heat input. The load is the ratio of the transferred heat to the design heat transfer of 41.5 gcal/hr. The curve is for operation with 90 percent blast-furnace gas and 10 percent oil. The graph shows also the efficiency at full load with pure oil firing. The difference between operation with oil and gas results from the higher waste gas quantity in the case of blast-furnace gas and has a corresponding influence on the efficiency at terminals as can be seen from the figures mentioned in the preceding.

Perfect operation of the heater is possible also at one quarter of the load as then four of the eight gas burners can be taken out of operation. The symmetrical arrangement of the burners ensures a virtually uniform charging of the radiation surfaces also in this case.

Table 1 Combustion Chamber Data of the "Haus Aden" and "Gelsenkirchen" Air Heaters

Plant	Haus Aden	Gelsenkirchen
Electric output, MW	6.37	17.25
Fuel	mine gas	blast-furnace gas
	hard coal	light fuel oil
Burners	5 combined burners for mine gas and pulverized coal	5 oil burners 8 blast furnace-gas burners
Cycle air:		
Mass flow, kg/sec	67	153
Inlet temperature, C	424	430
Inlet pressure, bar	31.8	40.5
Outlet temperature, C	681	714
Combustion chamber:		
Volume load, gcal/cu m hr	0.137	0.094
Cross-sectional load, gcal/sq m hr	1.37	1.36
Width over flats of tube lining, m	4.3	7.2
Tube length irradiated, m	10.0	13.5
Tube lining:		
Number of tubes	320	368
Tube dimensions, mm (od x wall thickness)	31.8 x 2.5[a]	40.8 x 5.0[a]
	31.8 x 3.0[a]	38.0 x 3.6[b]

[a] Austenitic steel with 16 percent Cr, 16 percent Ni, 2 percent Mo, Mn, Nb, Si.

[b] Austenitic steel with 19 percent Cr, 13 percent Ni, 10 percent Co, 3 percent Nb, W, Mo, Si, Mn.

a LP compressor
b intercooler
c HP compressor
d heat exchanger
e air heater
f turbine
g precooler

TOTAL HEAT ABSORPTION IN THE COMBUSTION CHAMBER

In all of the hitherto built air heaters, the radiation heating surfaces are arranged exclusively at the combustion-chamber walls. With this concept, the burned gas temperature at the combustion-chamber outlet must be below the fusion point of the ash to prevent serious slagging of the convection part. There are two methods of achieving this: increasing the radiation surfaces participating in the heat exchange or improving the radiation intensity of the flame.

Increasing the radiation surface, which means increasing the combustion chamber itself, is, in many cases, not compatible with the firing requirements. With regard to the stability of the flame particularly in the part-load range, the volume load has to be kept above a lower limit. This limit leads, in the case of increasing the plant and thus the combustion chamber, to an increasing cross-sectional load, and thus to higher tube wall temperatures. These phenomena are the cause of the similarly increased burned gas temperature at the combustion-chamber outlet.

In Table 1 these relationships are made clear by comparing the most important data of the combustion chambers of the "Haus Aden" and "Gelsenkirchen" plants. The cross-sectional load, i.e. the ratio of the total heat put into the combustion chamber to the cross section of the chamber, has remained unchanged. However, the volume load has decreased from 0.137 gcal/cu m hr at "Haus Aden" to 0.094 gcal/cu m hr at "Gelsenkirchen." This value is at the lower admissible limit. In spite of this, because of the low radiation intensity of the flame in the case of blast-furnace gas firing, the burned gas temperature at the combustion-chamber outlet reaches the upper limit which is still tolerable with regard to the convection surfaces that follow. Therefore, in laying out the "Gelsenkirchen" air heater, it was tried to widen the range limited by the admissible values for the minimum volume load and the maximum burned gas temperature at the combustion-chamber outlet, through carburization of the gas flame. Positive empirical values were available in the form of the results achieved with the "Haus Aden" plant (4, 6).

Therefore, the air heater for the "Gelsenkirchen" plant was laid out for normal operation with 90 percent blast-furnace gas and 10 percent fuel oil for carburization. The tests were made in order to justify the correctness of this solution and to determine the factors on which the total heat absorption in the combustion chamber is dependent. The aim of these tests is to develop — using also the results achieved with the "Haus

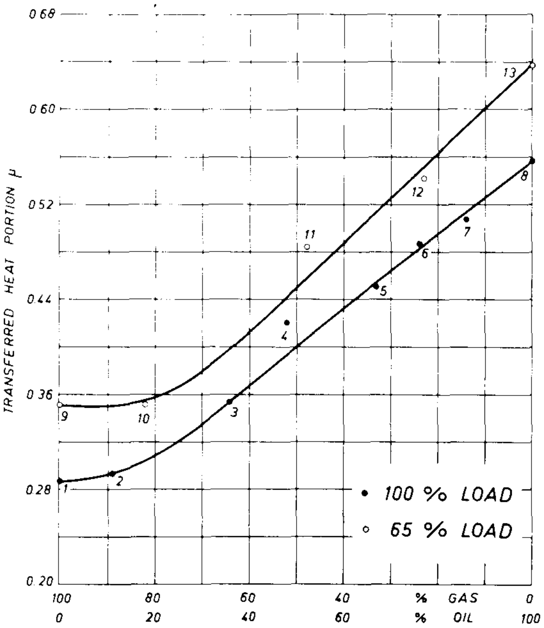
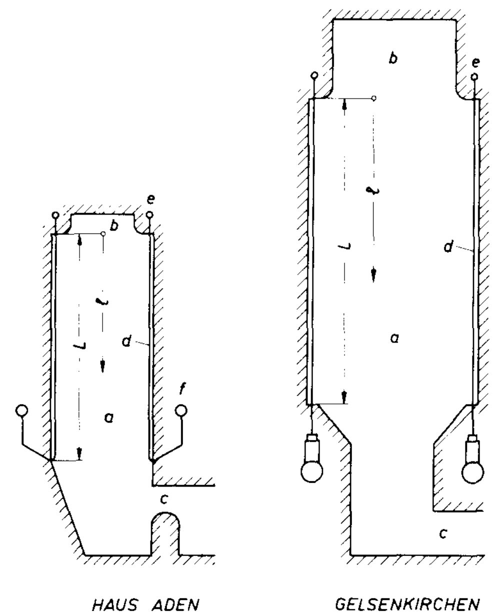


Fig.6 Transferred heat portion in the case of mixed-fuel firing



a	radiation chamber	d	tube lining
b	ignition muffle	e	inlet header
c	gas reversal pass	f	outlet header

Fig.7 Combustion chambers of the "Haus Aden" and "Gelsenkirchen" air heaters

Aden" plant — a method for calculating the total heat absorption in cooled combustion chambers of gas heaters in the case of mixed-fuel firing.

The measure of heat absorption in the combustion chamber as used in this connection is the transferred heat portion

$$\mu = \frac{Q}{Q_u} \qquad (1)$$

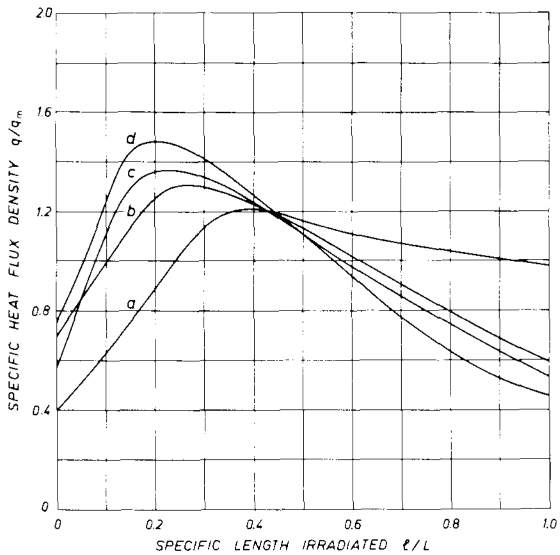
with Q standing for the heat radiated from the flame to the wall and Q_u for the heat put into the combustion chamber by the firing system. Q_u is calculated from the fuel quantities and the relevant lower calorific values and from the sensible heat, referred to 0 C, introduced by the combustion air and the blast-furnace gas.

Fig.6 shows the transferred heat portion, μ, as a function of the proportional fuel composition for full load and for a load of 65 percent. The average lower calorific value of the blast-furnace gas was 850 kcal/cu Nm[4] and that of the light fuel oil 10,165 kcal/kg. As can be seen from the graph, carburization of the blast-furnace gas flame with fuel oil hardly leads to an improved heat transfer in the combustion chamber if an oil portion of less than 10 percent at full load and less than 20 percent at partial load is put in. A marked increase in the amount of radiated heat is achieved only when raising the oil percentages beyond these values, in which case the curves rise almost linearly until their ends. The influence of the load is small in comparison with the influence of the fuel composition. For the tests, the results of which are shown in Fig.6, a constant excess-air coefficient of 1.15 was maintained. In order to name the different tests, Fig.6 shows also the test numbers.

From the previous measurements carried out at the "Haus Aden" plant, which is fired with mine gas and pulverized coal, there resulted a slightly different tendency of the curve of the transferred heat portion, μ, as a function of the fuel composition. With slight additions of coal to the mine-gas flame (10 to 20 percent), the influence of carburization is stronger than with high portions of coal. With increasing coal portions, the curve becomes flatter (4, 6).

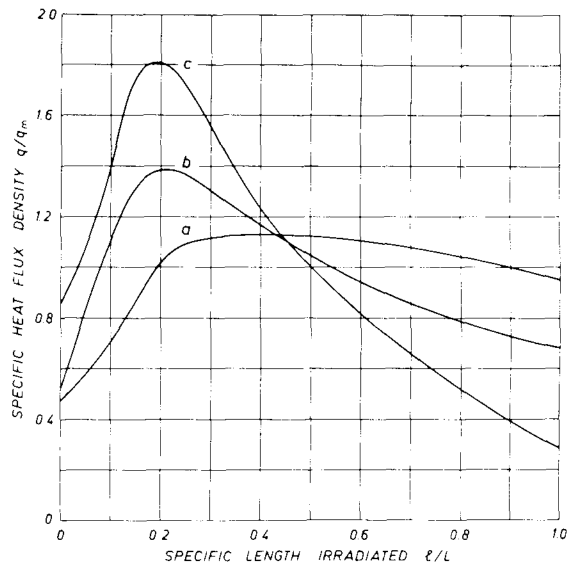
As far as the entirely different fuels permit a comparison, it can be said that the differences between the "Haus Aden" and the "Gelsenkirchen" results are partly due to the peculiarities of design of the two combustion chambers. Fig.7 shows the combustion chambers drawn to scale for comparison. Apart from the absolute difference in size, the over-proportionally increased ignition muffle of the "Gelsenkirchen" heater is evident. In addition, the design and arrangements of the burners differ widely. At "Haus Aden" combined burners for mine gas and pulverized coal were mounted in the roof of the ignition muffle

[4] 1 cu Nm = 1 cu m at 0 C and 760 mm-Hg.



a Test No. 1, gas/oil = 100/0
b Test No. 4, gas/oil = 52/48
c Test No. 6, gas/oil = 24/76
d Test No. 8, gas/oil = 0/100

Fig.8 Specific local heat flux density as a function of the specific length irradiated
Mixed-fuel firing and 100 percent load



a Test No. 9, gas/oil = 100/0
b Test No. 11, gas/oil = 48/42
c Test No. 13, gas/oil = 0/100

Fig.9 Specific local heat flux density as a function of the specific length irradiated
Mixed-fuel firing and 65 percent load

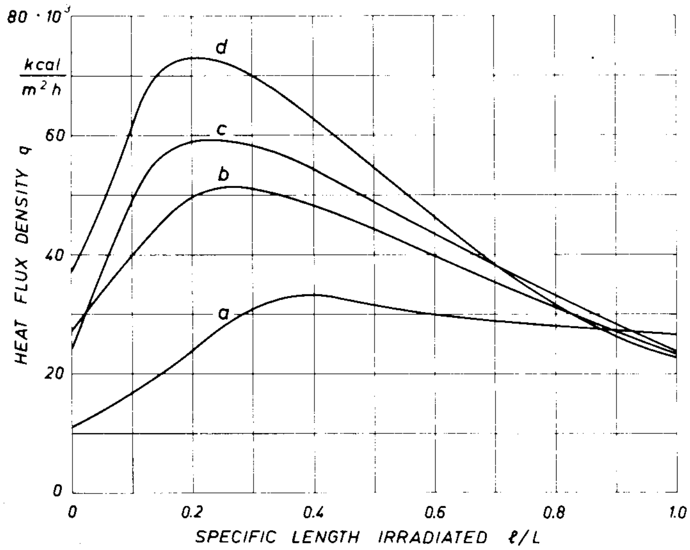
(4). At "Gelsenkirchen," the oil burners are arranged in the roof of the ignition muffle and the blast-furnace-gas burners in the walls of the ignition muffle in inclined position pointing downward (Fig.2). With small oil portions, the oil combustion is finished already in the ignition muffle, and the radiation conditions in the combustion chamber itself are practically not influenced. Only the temperature level of the burned gases is slightly raised by the higher theoretical combustion temperature, which leads to a slight increase in the flue-gas temperature also at the end of the combustion chamber. Only with larger oil portions, the flame enters the radiation part, thus enabling interactions between the gas flame and the oil flame.

The burned gas temperatures at the end of the combustion chamber in the case of pure oil firing are — despite of the very high theoretical combustion temperature — about 150 C lower than with pure blast-furnace gas firing. An essential reason for this is certainly the fact that the combustion times of oil and blast-furnace gas differ widely. The combustion of oil is brought to an end within a very short time, and during the cooling of the burned gas, there is no release of heat on the major part of its way through the combustion chamber. In contrary, the blast-furnace gas flame fills almost the entire combustion chamber. Heat release takes place parallel to heat transfer so that there are almost isothermal reactions. Although the temperature level is comparatively low, there is not sufficient time at the end of the combustion chamber for the pure cooling of the gas.

LOCAL IRRADIATION IN THE COMBUSTION CHAMBER

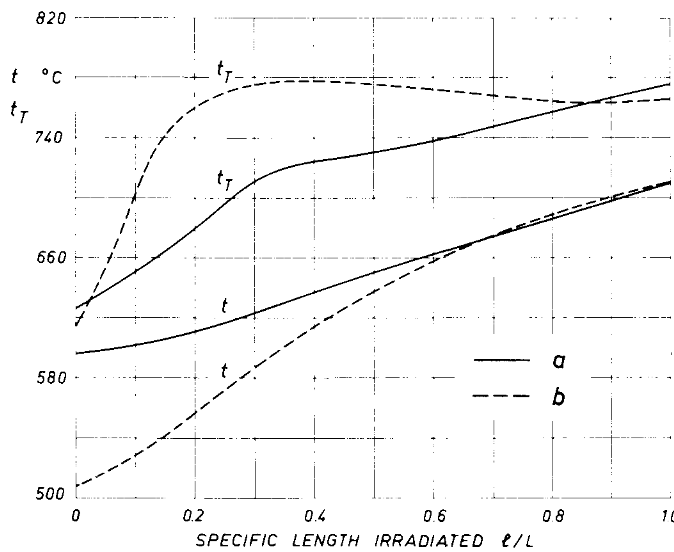
For the layout of the tube lining of the combustion chamber, it is necessary to know, apart from the total heat absorption in the combustion chamber, the local distribution of the heat absorption over the length of the chamber. The irradiation curve is calculated from the curve of the cycle air temperature plotted against the combustion-chamber length, as determined with the aid of the two measuring tubes.

A smooth curve is drawn between the measured temperature values. For the cycle air, the temperature increase is a clear measure of the enthalpy increase. The local irradiation is proportional to the differential quotient, $di/d(\ell/L)$, of the enthalpy, i, of the cycle air, which is calculated as a function of the specific length irradiated, ℓ/L. According to Fig.7, L is the total tube length under radiation and ℓ the running coordinate of the irradiation length. Thus, you get the local irradiation, q, referred to the mean value of the irradiation, q_m, as follows:



a Test No. 1, gas/oil = 100/0
b Test No. 4, gas/oil = 52/48
c Test No. 6, gas/oil = 24/76
d Test No. 8, gas/oil = 0/100

Fig.10 Absolute local heat flux density as a function of the specific length irradiated
Mixed-fuel firing and 100 percent load



a Test No. 1, gas/oil = 100/0
b Test No. 8, gas/oil = 0/100

t cycle air temperature
t_T tube wall temperature

Fig.11 Cycle air and tube wall temperatures when firing with fuel oil or blast-furnace gas

$$\frac{q}{q_m} = \frac{di/d(\ell/L)}{i_1 - i_0} \qquad (2)$$

In this formula, i_0 and i_1 are the specific enthalpies of the cycle air at the inlet and outlet of the combustion chamber.

The mean irradiation in the combustion chamber is calculated from the equation

$$q_m = \frac{(i_1 - i_0) \cdot M}{A} \qquad (3)$$

with the enthalpies i_0 and i_1 as in equation (2), the total mass flow of cycle air, M, passing through the combustion chamber tubes, and the total area, A, of all combustion chamber tubes calculated from the outer diameter.

In Fig.8, the specific local heat flux density, q/q_m, is shown as a function of the specific length irradiated, ℓ/L, for full load with different fuel mixtures. For comparison with Fig.6, the legend contains again the test numbers. The test results from "Haus Aden" (4, 6) are confirmed in tendency: With increasing oil portion, the maximum of the specific irradiation curve rises and, at the same time, is shifted toward the burners. With pure oil firing, the excess over the mean value amounts to almost 50 percent; with pure gas firing, it is only about 20 percent.

The curves of the specific heat flux density for an air heater load of 65 percent are shown in Fig.9. The irradiation curves for partial load are slightly raised in the vicinity of the burners as compared with those at full load. With a high oil portion, the maximum at partial load is more distinctive. However, for blast-furnace gas, the height of the maximum is practically not influenced by the load.

The local stress on the tube wall depends on the absolute local irradiation. This results from the total heat transferred in the combustion chamber, of which the transferred heat portion μ (Fig 6) is a measure, in connection with the curves in Figs.8 or 9. The resultant local heat flux density is shown in Fig.10 as a function of the specific length irradiated. The graph is representative for the same tests as Fig.8. The area below the curves is a measure of the particular total heat absorption in the combustion chamber.

As can be seen from Fig.10, the absolute irradiation at the end of the combustion chamber is practically independent of the gas/oil portions, although in the case of oil firing the burned gas temperatures at this place are about 150 C below those in the case of gas firing. In the first approximation, it may be assumed that at the end of the combustion chamber there is pure gas radiation.

The radiant components in the burned gas in the case of oil firing are about 12 percent CO_2 and 11 percent H_2O and in the case of gas firing 25 percent CO_2 and 3 percent H_2O. In the temperature range under consideration, approximately 1000 C, with equal zone thicknesses and concentrations, the radiation of water amounts to almost twice the value of carbon-dioxide. Hence, the emission capacity of the burned gas in the case of oil firing is about 50 percent higher than it is with blast-furnace gas firing. This fact, in conjunction with the smaller burned gas quantity in the case of oil firing (the same amount of heat transferred means a higher degree of burned-gas cooling in the case of oil firing than in the case of gas firing), is the reason for the steeper fall of the irradiation curve with oil firing.

The irradiation curves measured at the "Haus Aden" plant could be represented with close approximation by a Gaussian distribution curve (bell-shaped curve), with the location of the maximum mainly described by the burned gas velocity and the width of the curve (height of maximum) by the ratio of the theoretical combustion temperature to the burned gas temperature at the combustion-chamber outlet (4, 6). The results of the measurements at the "Gelsenkirchen" plant were predicted correctly in their tendency by this method. Regarding the special form of the curve, there are some deviations. The Gaussian curve requires a symmetrical distribution of the irradiation relative to the irradiation maximum. The curves measured at "Gelsenkirchen" are, however, asymmetrical. The combustion chamber is laid out for pure gas firing, pure oil firing, and any desired mixture of these fuels. This makes compromises unavoidable. For pure gas firing, the size of the chamber is just sufficient. The flame extends as far as the end of the radiation room. This means almost isothermal processes in the combustion chamber except in the heating-up zone near the burners. Accordingly, the rear part of the irradiation curve is rather flat. With pure oil firing, combustion at the outlet of the very large ignition muffle (Fig.7) is nearly finished, which results in a correspondingly high irradiation at the beginning of the tube. As mentioned in explaining with the total heat absorption, the volume load for pure oil firing is far below the usual values (Table 1). To achieve conditions comparable to those at the "Haus Aden" plant, it would be necessary, for oil firing, to subdivide the chamber theoretically into a pure combustion room and a radiation room following the combustion room. However, for blast-furnace gas firing a corresponding radiation room would have to be added to the existing combustion chamber.

TUBE WALL TEMPERATURES

For reliable operation of a gas heater, the tube wall temperatures arising in operation are very important. With the total heat absorption in the combustion chamber, the temperature at which the cycle air enters the combustion chamber is given, as the outlet temperature is given by the turbine inlet temperature. The shape of the curve of the cycle air temperatures between these two points is fixed according to the curve of the local irradiation. With the cycle air temperature then known for each point of the tube and with the relevant local heat flux density you can, by applying the known laws of heat transfer, calculate the relevant tube wall temperature. In this calculation, the nonuniform distribution of the irradiation over the tube circumference is taken into account (7).

Fig.11 shows, for the two extreme cases of pure blast-furnace gas firing and pure oil firing at full load, the curves of the cycle air and tube wall temperatures. These curves are based on the curves of the specific heat flux densities, a and d, in Fig.8. The tube wall temperature plotted is the maximum value on the tube side facing the flame. This temperature is taken as the basis for the stress calculation of the tube.

With pure gas firing, the tube wall temperature rises from the lowest value at the beginning of the tube continuously to its maximum value which, in this case, is reached at the tube end. However, with pure oil firing, the tube wall temperature reaches its maximum, after a steep rise at the beginning of the tube, already at one-third of the radiated tube length. Toward the end of the tube the temperature decreases slightly. As was to be expected from Fig.10, the tube wall temperatures at the end of the combustion chamber are almost equal for both methods of firing. A comparison of the tube wall temperatures shows that, in the case of oil firing, it has made better use of the material than in the case of blast-furnace gas firing.

The temperature curves for mixed-fuel firing are situated between the extreme values. From this, it can be concluded that the addition of oil is possible up to high portions without raising the maximum tube wall temperature.

SUMMARY

The overall efficiency of the "Gelsenkirchen" plant, ascertained by measurements, is in accordance with the layout data.

The transferred heat portion, μ, in the case of pure oil firing is almost twice that in the

case of pure gas firing; the influence of the load is comparatively small.

The empirical method of calculating the heat irradiation curve, as developed by tests at the "Haus Aden" plant, was suitable to predict the conditions at the "Gelsenkirchen" plant in their tendency. Deviations result from the different proportions of the combustion chambers and the differences in the design and arrangement of the burners.

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