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FURNACE TEMPERATURE MEASUREMENTS AT
BOUNDARY DAM POWER STATION
ESTEVAN, SASKATCHEWAN
JANUARY 22-23, 1975

by

F.D. Friedrich and A.C.S. Hayden
Canadian Combustion Research Laboratory
Energy Research Laboratories

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INTRODUCTION

Under a contract (Job 4013) arranged with the Director of Thermal Generation for Ontario Hydro, staff of the Canadian Combustion Research Laboratory (CCRL) carried out measurements of flue gas temperatures in the furnace of a lignite-fired boiler at the Boundary Dam Power Station of the Saskatchewan Power Corporation. The purpose was to help establish furnace design criteria for boilers fired with Estevan lignite, where the fouling of heat-exchange surfaces by low-melting-point constituents in the ash is a perennial operating problem. This report briefly describes the boiler, the conditions under which the temperature measurements were carried out, and the results obtained. Some comments on the evaluation of ash fusion characteristics are also offered, and the suction pyrometer used for measuring the gas temperatures is briefly described in an appendix.

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DESCRIPTION OF THE BOILER

The temperature measurements were carried out on Boiler No. 5, which is block-coupled to a 150 MW turbogenerator unit. The boiler was built by Combustion Engineering-Superheater Ltd. of Montreal. It incorporates steam superheat and reheat, and utilizes the C-E tangentially-fired combustion system. The fuel is lignite from the Utility Coal Mine near Estevan. Small amounts of natural gas are also fired intermittently. Design rating of the boiler is 1,050,000 lb of steam per hour, operating pressure of 1900 psig, with both superheated and reheated steam temperatures of 1005°F. Design furnace heat release rates are 63,200 Btu/sq ft hr and 13,540 Btu/cu ft hr.

DESCRIPTION OF TEST CONDITIONS

In lignite-fired boilers, the most critical zone with respect to fouling is usually at the furnace exit, where the flue gases pass through the first tube banks of heat exchange surface. Since the purpose of the tests was to relate flue gas temperatures to fouling characteristics, measurements were carried out at the top of the furnace, just below the superheater platen assemblies, where access to the furnace by a temperature probe was possible through a series of 3 in. pipe nipples in the furnace sidewalls. Figure 1 shows a side section of the upper part of the boiler, with arrows marking the ports used. Flue gas temperatures were measured by means of a suction pyrometer, which is described in the appendix. Unfortunately, sections of guard rail had to be cut out to provide access to the ports. For this reason, as well as because of difficulties in providing cooling water for the suction pyrometer, measurements were limited to one boiler, No. 5.

The boiler is operated with a generally continuous schedule of soot blowing. This means that the soot blowers are automatically operated in sequence, according to an adjustable cycle, and one cycle follows the other more or less without interruption. Generally, the furnace wall blowers are operated every two to three hours, while the travelling soot blowers in the superheater and reheater tube bundles are operated every three to five hours. With one exception, which will be discussed later, temperature measurements were carried out immediately after the wall blowers and superheater/reheater blowers had been operated, and the cycle was interrupted until a set of measurements had been completed.

RESULTS

Traverse 1

These measurements were taken with the boiler operating under near-normal conditions, with the burner tilt under automatic control. A small amount of natural gas was being fired. The furnace walls, superheater and reheater had just been cleaned by means of the soot blowers. A malfunctioning feedwater control valve limited output to about 140 MW.

Figure 2 summarizes the operating conditions and the temperature data obtained. Of the isotherms shown, it must be recognized that the area inside the 2300°F isotherm is somewhat conjectural. It is also possible that temperatures higher than those shown existed near the centre of the furnace, although it seems unlikely that they would have exceeded 2400°F. However, it is clear that temperatures were fairly uniform and gradients were gentle, but the left side of the furnace was running perhaps 75° hotter than the right side. This could be due to non-uniform fouling of the furnace walls.

Traverse 2

These measurements were taken with the boiler generating 145 MW while burning coal only. All burners were tilted to their maximum downward position, and the soot blowers on the furnace walls and in the superheater and reheater sections were operated just prior to the measurements.

Figure 3 summarizes the operating conditions and temperature data. In this case temperatures were generally 150°F higher than in Traverse 1, at least in the left half of the furnace. The tendency for the left side to run hotter than the right side is also more apparent, and it appears likely that there is a sizeable zone where temperatures were 2400°F or more, somewhat left of the furnace centreline.

Effect of Burner Tilt

From the results of the two traverses just discussed, it appeared likely that the highest temperatures at the plane of measurement consistently occurred at the left side of the furnace. It therefore seemed that useful information could be obtained by taking further measurements through the centre port on the left side only. This had the further advantage that sets of readings could be obtained quickly, without substantially interrupting the normal soot-blowing cycle. To evaluate the effect of burner tilt on flue gas temperature entering the superheater, two sets of measurements were carried out, one with all burners tilted fully down, and one with all burners tilted more or less fully up. Again all wall, superheater and reheater soot blowers were operated prior to each set of measurements. The operating conditions and temperature data are shown in Figure 4. Adjusting burner tilt from fully down to fully up raised the flue gas temperature by about 50°F, except near the wall, where the temperature rose 100°F.

Effect of Soot blowers

To establish the effect of operating the wall soot blowers on flue gas temperature at the furnace exit, two sets of measurements were carried out, again through the centre port on the left side of the furnace. The first set was taken just prior to the normal cycle of wall blower operation. Then the wall, superheater and reheater blowers were operated, and a second set of measurements were taken. The burners were tilted up for both sets. Figure 5 summarizes the operating conditions and the temperature measurements. It can be seen that with dirty walls, the flue gas reached a fairly high temperature: 2420°F. Operating the soot blowers reduced the gas temperature by about 70°F.

EVALUATION OF ASH FUSION CHARACTERISTICS

The most common criterion of coal ash fusion characteristics is the ASTM Method No. D1857/68 for Fusibility of Coal and Coke Ash. The test is usually carried out in a chemically reducing atmosphere because most coals exhibit a lower ash fusibility under reducing conditions than under oxidizing conditions, primarily due to the influence of iron compounds. Ferrous compounds generally have lower melting temperatures than ferric compounds. The former predominate in reducing conditions, while the latter predominate in oxidizing conditions. The furnace atmosphere in most boilers is mainly oxidizing, but designs are usually based on the ash fusibility under reducing conditions, with the higher fusibility due to oxidizing conditions serving as a margin of safety.

The ASTM procedure, conducted in a reducing atmosphere, gives the following values for Estevan Lignite from Utility Coals Ltd*

Initial deformation	2040°F
Softening temp., spherical	2130°F
Softening temp., hemispherical	2350°F
Fluid	2500°F

Other samples from the same area have shown hemispherical softening and fluid temperatures as much as 100°F lower. In a boiler, some sintering can be expected in regions where gas temperatures reach the spherical softening temperature, and rapid deposition can be expected in regions where gas temperatures reach or exceed the hemispherical softening temperature. Nearly all the temperatures measured were above the spherical softening temperature, and some were within 100°F of the fluid temperature. Thus the potential for fouling appears to be substantial. This is confirmed by the rapidity with which ash deposits built up on the refractory tip of the suction pyrometer. Often a one-inch layer would form on the upstream side of the tip in the course of five minutes. In one instance the deposit was so large that the tip could not be withdrawn through the 3-in. access port, and had to be broken.

The deposits on the pyrometer tips were of two distinct types. That on the outside looked like a typical lignite sinter; dark grey in colour, porous, bulky and fairly hard. However, inside the gas passages of the tip was a thin layer of hard, translucent glassy material that had obviously been fairly fluid at the measured temperatures. At the inner end of the tip passages the gas flow had occasionally spun it out into filaments resembling mineral wool insulation. This points up the fact that coal ash is a mixture of materials having varying melting temperatures, and the ASTM ash fusion test, which determines only the average properties of the mixture, is an inadequate guide for predicting fouling potential. If a small proportion of the ash becomes sticky at relatively low temperatures, fouling problems may develop even though the bulk of the ash has a substantially higher softening temperature.

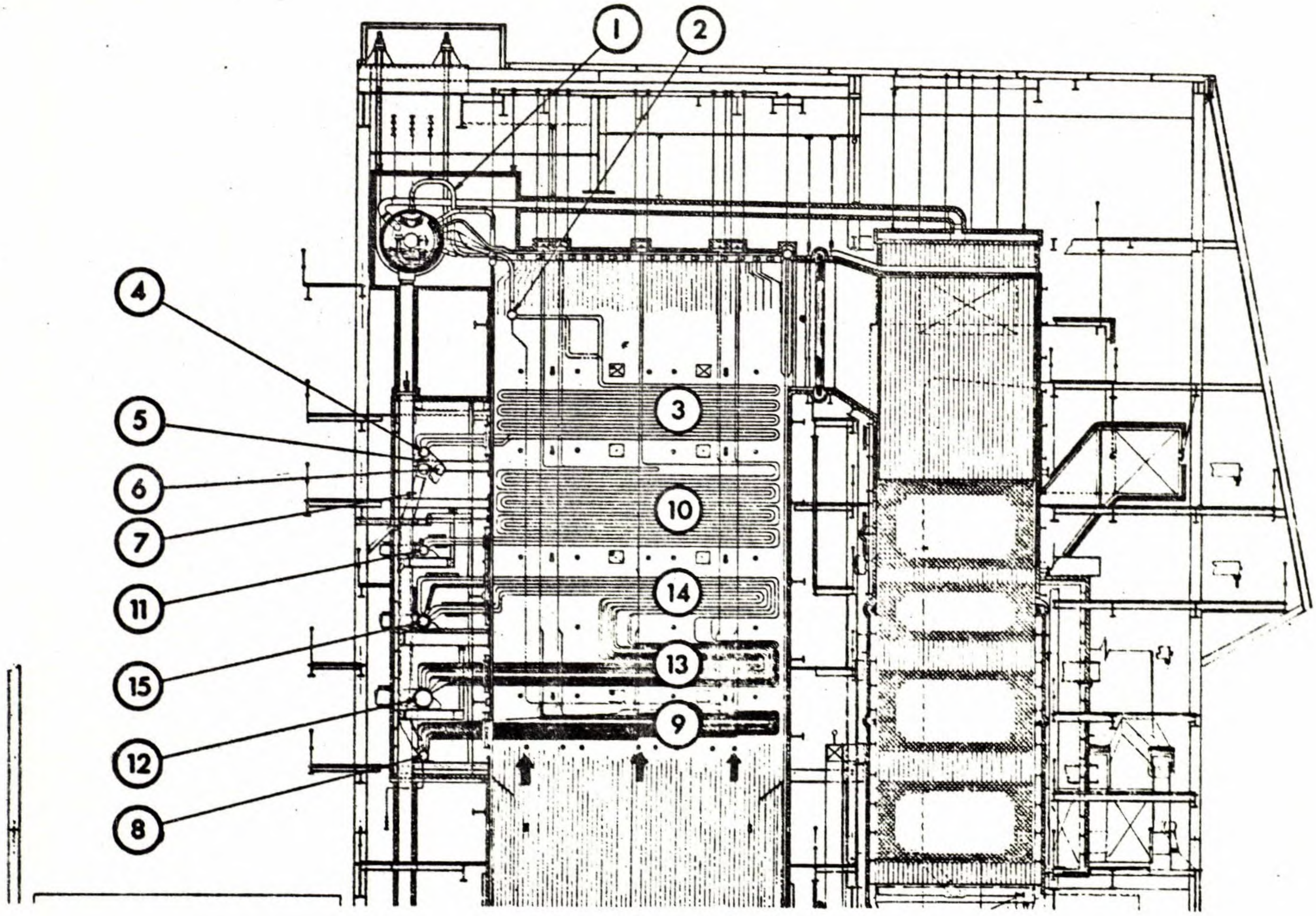
**T.E. Tibbetts and W.J. Montgomery, "Evaluation of Canadian Commercial Coals: 1972 Saskatchewan, Alberta and British Columbia". Information Circular IC305, Fuels Research Centre, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada April 1973.*

When designing a boiler for a coal which is apt to present fouling problems, the ash fusion characteristics of the coal should be very carefully studied, not only by means of the ASTM ash fusion determination, but by means of a heated-stage microscope, so that the presence of low-melting phases can be detected. Furthermore, it is desirable to use ash samples from a prototype firing system, rather than samples prepared by ashing coal in a muffle oven. This is because the higher temperatures encountered in the prototype furnace may change the chemical composition of the ash, and thus change the fusion characteristics.

Ash fusion characteristics may also vary substantially with location in the seam; therefore, a comprehensive sampling program is desirable. Some attention should also be given to the overburden adjacent to the coal seam. If, for example, the coal is found to have a softening temperature of 2350°F, but the immediate overburden contains a phase which melts at 1800°F, then selective mining techniques will be necessary.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the staff of Boundary Dam Power Station for their co-operation during the tests, particularly Mr. John Haines, station superintendent, and Mr. John Stevenson, results engineer. Thanks are also due to Mr. Ronald Smith of Ontario Hydro for his assistance and advice.



SUPERHEATER MK. NO.	QUANTITY	SIZE	DESCRIPTION
1	13	5" O.D.	Superheater (SH) Connecting Tube
2	1	10 3/4" O.D.	SH Horizontal Spaced Upper Inlet Header
3	88	1 3/4" O.D.	SH Horizontal Spaced Upper Assemblies @4½ Ctrs
4	1	10 3/4" O.D.	SH Horizontal Spaced Upper Outlet Header
5	2	12 3/4" O.D.	SH Links to Desuperheater
6	2	12 3/4" O.D.	Spray Type Desuperheater
7	2	12 3/4" O.D.	SH Links from Desuperheater
8	1	10 3/4" O.D.	SH Horizontal Platen Inlet Header
9	22	1 1/2" O.D.	SH Horizontal Platen Assemblies @18" Ctrs.
10	44	2 1/8" O.D.	SH Horizontal Spaced Lower Assemblies @9 Ctrs.
11	1	12 3/4" O.D.	SH Horizontal Spaced Lower Outlet Header
REHEATER			
12	1	22" O.D.	Reheater (RH) Horizontal Platen Inlet Header
13	22	2" & 2¼" O.D.	RH Horizontal Platen Assemblies @ 18" Ctrs.
14	44	2" & 2¼" O.D.	RH Horizontal Spaced Assemblies @ 9" Ctrs.
15	1	16" O.D.	RH Horizontal Spaced Outlet Header

Figure 1. Side section of upper part of boiler, showing location of convective heat exchange surface and ports used for flue gas temperature measurements (Courtesy Saskatchewan Power Corp).

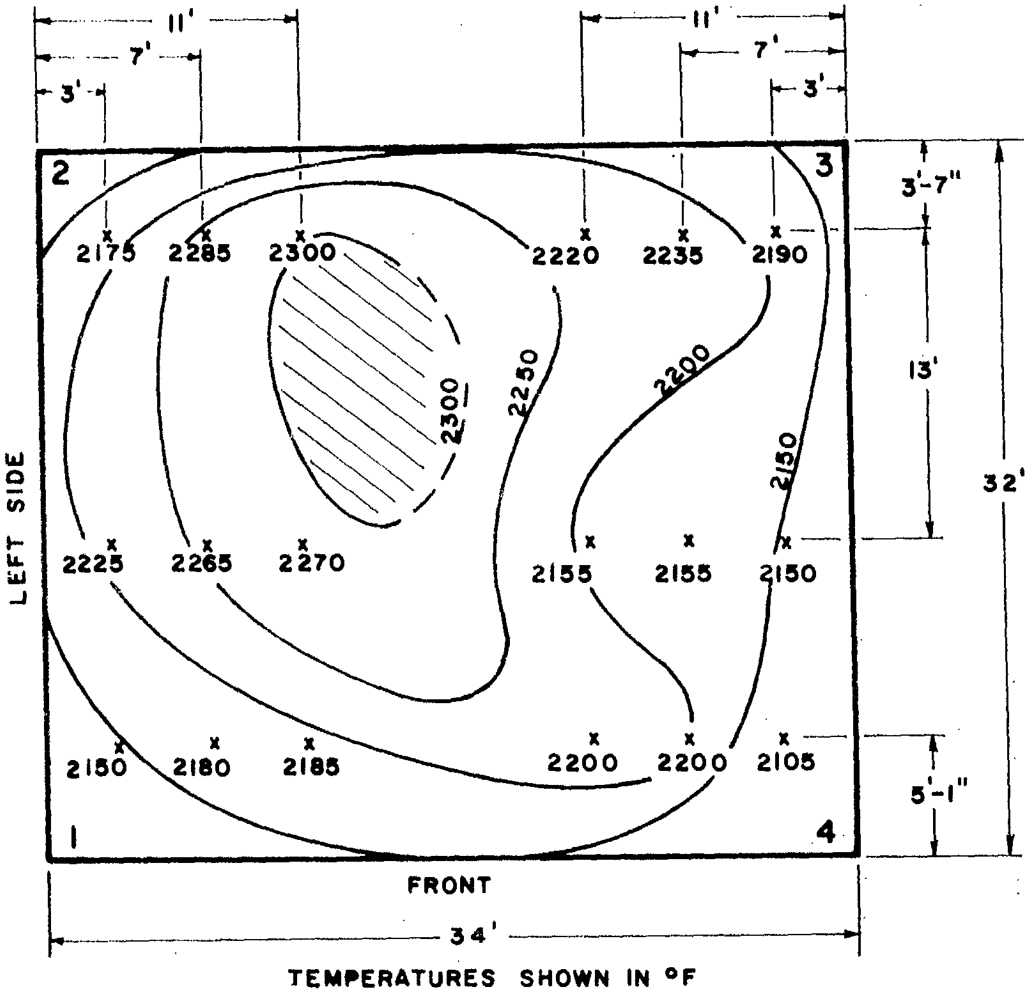
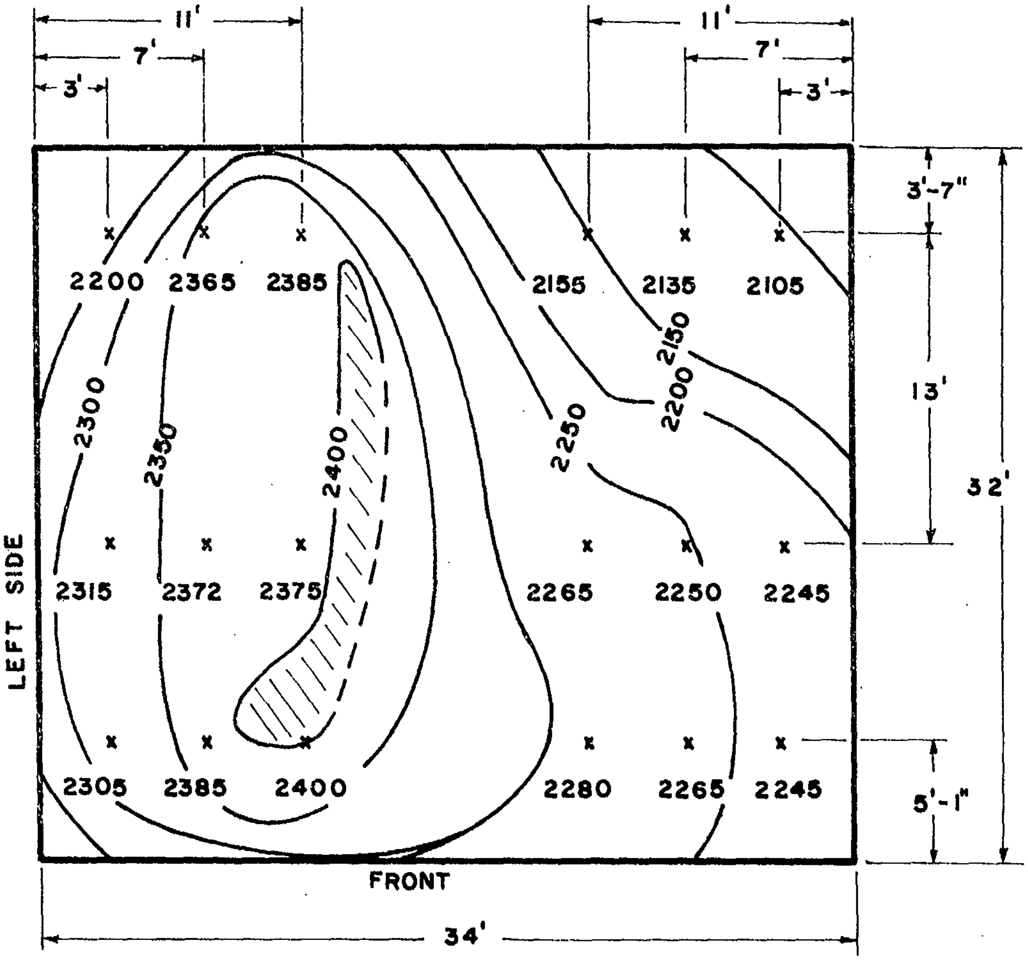


Figure 2. Temperature Traverse 1, 1015 hr to 1130 hr, Jan 22/75
Furnace cross-section at plane of measurements.

Load:	140 MW
Main Steam Flow:	840,000 lb/hr
Main Steam Pressure:	1830 psi
Main Steam Temperature:	990°F

Excess O_2:	4.5%
Fuel:	Coal + 9000 cfh Natural Gas
Burner Tilt:	No. 1 Down 5°
	No. 2 Down 25°
	No. 3 Down 30°
	No. 4 Down 20°

All furnace soot blowers operated prior to start of test.



TEMPERATURES SHOWN IN °F

Figure 3. Temperature Traverse 2, 1415 hr to 1545 hr, Jan 22/75
Furnace cross-section at plane of measurements

Load: 145 MW
Main Steam Flow: 890,000 lb/hr
Main Steam Pressure: 1800 psi
Main Steam Temperature: 1010°F

Excess O_2: 4.3%
Fuel: 100% coal
Burner Tilt: All Burners Down 30°

All furnace soot blowers operated prior to start of test.

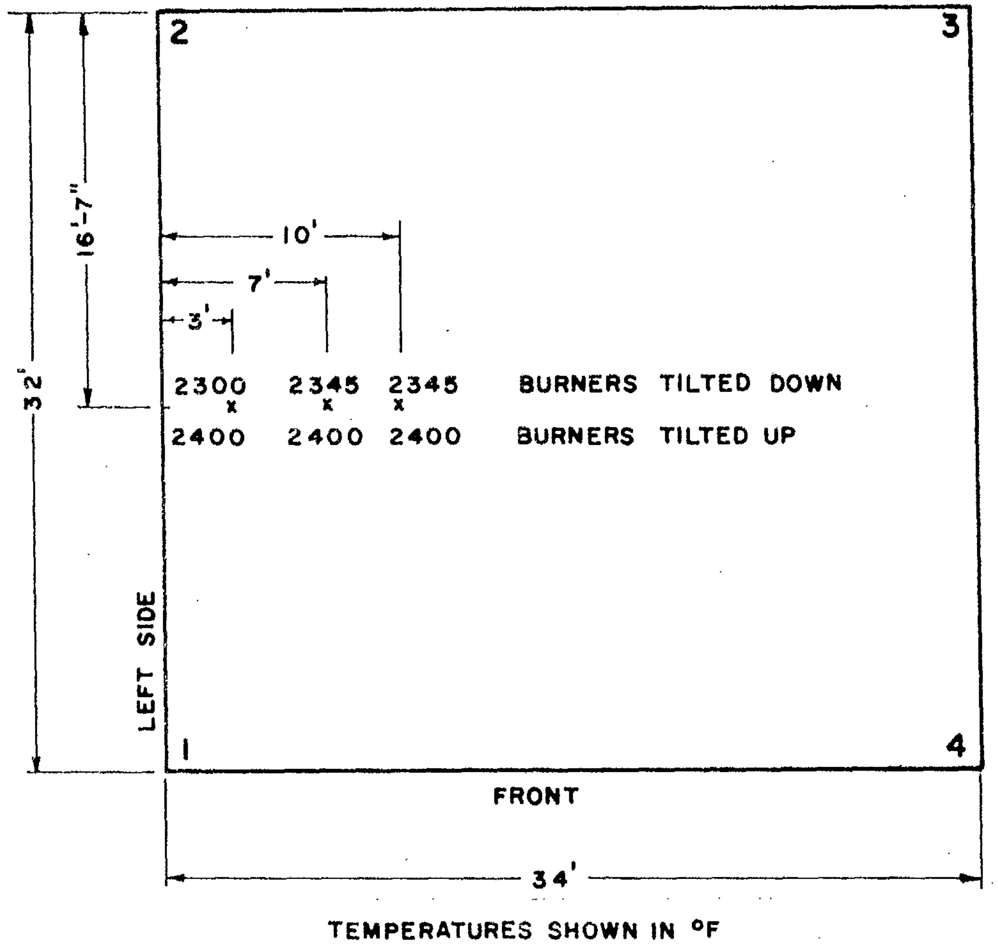
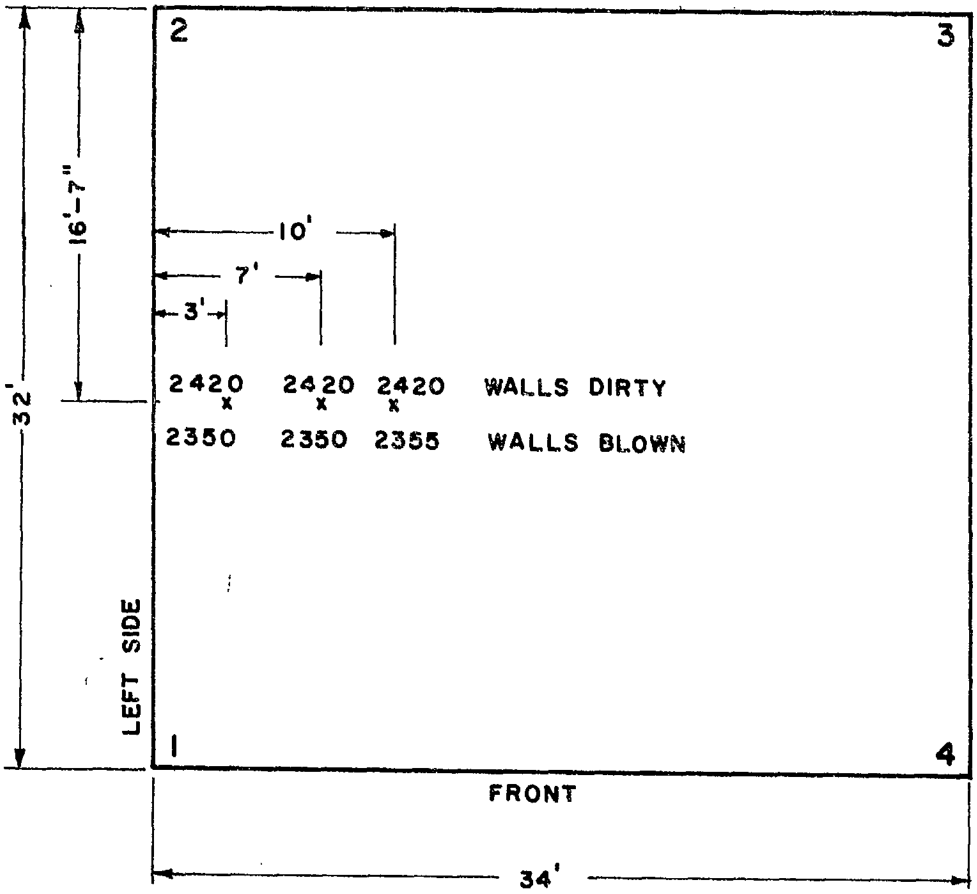


Figure 4. Effect of burner tilt on furnace gas temperatures. Furnace cross-section at plane of measurements.

Burners Tilted Down	Burners Tilted Up	
0925 hr to 0931 hr, Jan 23/75	1059 hr to 1103 hr, Jan 23/75	
Load: 140 MW	Load: 140 MW	
Excess O_2: 3.5%	Excess O_2: 3.0%	
Fuel: 100% coal	Fuel: 100% coal	
All Burners Down 30°	Burner No. 1: Up 23°	Burner No. 2: Up 28°
	Burner No. 3: Up 24°	Burner No. 4: Up 23°

All furnace soot blowers operated prior to each set of measurements.



TEMPERATURES SHOWN IN °F

Figure 5. Effect of soot blowing furnace walls on furnace gas temperatures. Furnace cross-section at plane of measurements.

<u>Walls Dirty</u>	<u>Walls Clean</u>
1503 hr to 1508 hr Jan 23/75	1553 hr to 1557 hr
Load: 140 MW	Load: 140 MW
Fuel: 100% coal	Fuel: 100% coal
Burner No. 1:Up 23° Burner No. 2:Up 28°	Burner No. 1:Up 23° Burner No. 2: Up 28°
Burner No. 3:Up 24° Burner No. 4:Up 23°	Burner No. 3:Up 24° Burner No. 4: Up 23°
Furnace walls due for normal soot blowing cycle.	All furnace soot blowers operated just prior to measurements.

APPENDIX

SUCTION PYROMETERS IN THEORY AND PRACTICE

by

T. Land, M.A., F.Inst.P., and R. Barber, B.Sc., F.Inst.P.

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Suction Pyrometers in Theory and Practice

By T. Land, M.A., F.Inst.P.,
and R. Barber, B.Sc.

SYNOPSIS

Details are given of the precautions necessary to obtain accurate readings with a suction pyrometer. The pyrometer must be designed with an adequate number of radiation shields, and the number necessary under different conditions is shown in the tables and graphs. A high gas velocity is desirable and the means of obtaining it are discussed. In the open-hearth furnace uptake, conventional pyrometers suffer from the effects of overheating and slag attack. Mayorcas and Burton have proposed a pyrometer in which the radiation shield system is enclosed in a water jacket, and this design appears to be the best for such difficult applications. Rigorous methods are described for estimating the error of a pyrometer in use. A pyrometer designed on the basis of the theoretical and experimental work is described and illustrated. 1154

SUCTION PYROMETERS are beginning to be used for routine measurements in steelworks, particularly for measuring the temperature of the preheated air in the uptakes of open-hearth furnaces. There seems to be a need for a clear and simple statement of the basic features which must be incorporated in the design of a suction pyrometer to ensure a given degree of accuracy; there is also a need for simple but rigorous methods of assessing the error of a pyrometer while it is being used. We have recently published[1] a mathematical analysis of the problem of the suction pyrometer together with details of experiments made to test the accuracy of the theory. The purpose of the present paper is to give in a simple form the results of this work, in the hope that it may provide some practical guidance on the measurement of gas temperatures in steelworks.

It is not easy to measure the temperature of the hot gas, particularly if its surroundings are at a very different temperature. A sheathed thermocouple, placed in the gas, takes up a temperature much nearer to the temperature of the surrounding surfaces than to that of the gas. This is because, at high temperatures, the radiant heat-transfer coefficient between the thermocouple and its surroundings is so much larger than the convective heat-transfer coefficient between the thermocouple and the gas. To measure the true gas temperature, the thermocouple must be isolated very carefully from radiation received from the brickwork, usually by surrounding the thermocouple with a series of concentric radiation shields. At the same time the convective heat transfer to the thermocouple is greatly increased by sucking the hot gas past the thermocouple and the radiation shields at a high velocity. In this way, it is possible to reduce the effect of the radiant heat from the brickwork to negligible proportions, and to ensure that the pyrometer measures the true temperature of the hot gas.

Table I

EFFICIENCY (%) FOR SHEATHED THERMOCOUPLES WITH MULTIPLE RADIATION SHIELDS OF BLACKENED METAL

Gas velocity 500 ft/s

Temperature, C	Number of Radiation Shields									
	1	2	3	4	5	6	7	8	9	10
400	98									
600	88	98								
800	71	93	98							
1000	54	81	93	97	99					
1200	39	69	85	92	95	98	99			
1400	28	55	74	83	91	95	97	99	99	
1600	20	43	62	73	83	90	94	96	97	98

In theory this sounds simple and straightforward, but in a practical case how should a pyrometer be designed for a particular application? How many radiation shields will be necessary and what gas velocity should be used? There is no great difficulty in making a pyrometer which gives a reading of some kind, but the problem of designing a pyrometer to give a specified performance is not particularly easy. Little help is available from text books, and the British Standard Code for Temperature Measurement is noticeably reticent. It is hoped that the principles set out in the present paper may give useful and practical guidance on the design of suction pyrometers.

DESIGN AND EFFICIENCY

The accuracy of a suction pyrometer depends on the difference in temperature between the gas and the surroundings of the pyrometer. For this reason it is not possible to state the accuracy of a pyrometer of conventional design as 'so many degrees Centigrade.' If no gas is sucked past the thermocouple and the radiation shields the pyrometer will have a certain error; when gas is aspirated past the couple and shields a certain fraction of this error will be eliminated; we will call this fraction 'the efficiency of the pyrometer.' This concept of 'efficiency' is of fundamental importance to the accuracy of suction pyrometers. If the conditions at the point of measurement are such that a simple sheathed thermocouple registers a temperature within 25° C of the true gas temperature, then a suction pyrometer with an efficiency of only 80% would reduce the error to 5° C; but if conditions were such that the error of

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Manuscript received 20th April, 1955.

Mr. Barber is in the Research Department of Land Pyrometers Ltd., Sheffield, of which Mr. Land is Managing Director.

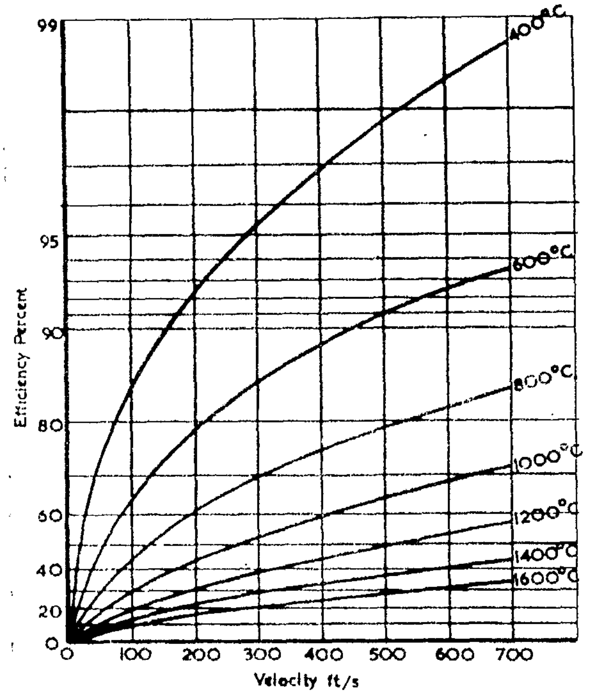

Fig. 1—Efficiency of pyrometer with blackened metal sheath and one shield

the sheathed couple was 250° C, a pyrometer with an efficiency of 98% would be necessary to obtain the same absolute accuracy.

In designing a suction pyrometer the first question to decide is how many radiation shields will be needed. The number of radiation shields depends mainly upon the temperature at which the pyrometer is operating. The efficiency of a sheathed thermocouple with one radiation shield at different gas velocities and different temperatures is shown in Fig. 1. The curves have been drawn on the assumption that the pyrometer sheath and the radiation shields are all of oxidized metal having a high emissivity and a high thermal conductivity. It will be seen that a simple pyrometer of this kind is useful only at temperatures up to about 500° C. When two concentric radiation shields are placed around the sheathed thermocouple the efficiency is considerably improved, as Fig. 2 shows, and such a pyrometer will give accurate results up to about 800° C. At higher temperatures it is necessary to use large numbers of radiation shields and the efficiency of pyrometers with multiple shields is shown in Table I. It is clear that four or five simple radiation shields are desirable at 1000° C and five or six shields at 1200° C. This result fully agrees with Marsh[2] who found it necessary to use a suction pyrometer with five concentric nickel radiation shields to measure the temperature of the preheated air in an open-hearth furnace.

Table I is calculated for a gas velocity through the radiation shield system of 500 ft/s. If the gas velocity is less than 500 ft/s the pyrometer will operate less efficiently and as if it had a smaller number of radiation shields. This is indicated in Table II, from which it will be seen that if the gas velocity were 100 ft/s the pyrometer would have only the same efficiency as one with only half the number of radiation shields operating at the full velocity of 500 ft/s.

These tables and graphs summarize the results of numerous calculations and experiments, and the inevitable conclusion is that it is relatively easy to measure gas temperatures of 500° or 600° C, but at 1000° C a pyrometer of some complexity is needed, using multiple radiation shields and a high gas velocity. This fact has usually been understood by those who have measured gas temperatures in the open-hearth furnace, but it may be worth emphasizing once again now that suction pyrometers are beginning to be used more widely in the steel industry.

Refractory radiation shields are necessary at high temperatures and although they are fragile and require fairly frequent replacement they have the compensating advantage that clean refractory surfaces have lower emissivities than most oxidized metals. As a result, it has been shown both in theory and in practice that each refractory radiation shield when new and clean may be equivalent to two or even three oxidized metal shields, and pyrometers with only two refractory shields have been used with fair efficiency in open-hearth uptakes. It is important to remember that this efficiency depends greatly on the low value of the emissivity of the refractory surfaces; after a period of use the surfaces may become contaminated and the emissivity may rise, and if this happens the efficiency may be seriously impaired. Refractory radiation shields must therefore be used with caution.

BARE THERMOCOUPLES AND COMPLEX RADIATION SHIELDS

In some applications the bare thermocouple wires may be exposed to the gas in the radiation shields.

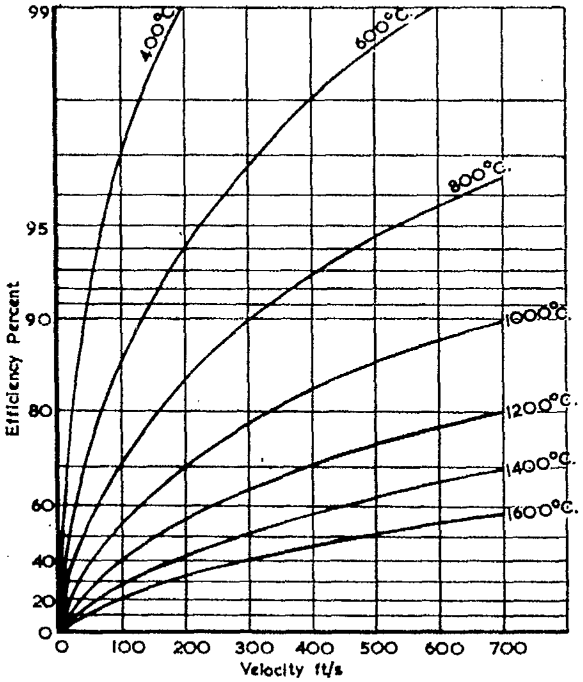

Fig. 2—Efficiency of pyrometer with blackened metal sheath and two shields

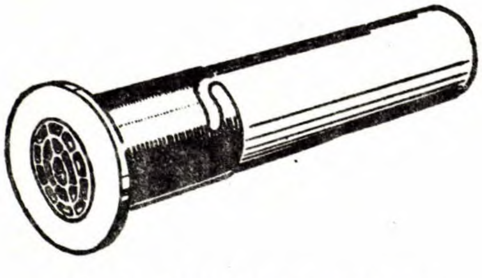

Fig. 3—Type 4*B* refractory hood

If the gas velocity is no more than 100 ft/s the use of a bare base-metal thermocouple does not greatly improve the efficiency of the pyrometer, but at 500 ft/s it may be equivalent to adding an extra radiation shield to the system. Occasionally, the gas is clean enough for a bare platinum thermocouple to be used and the error of the pyrometer may then be reduced by a factor between 5 and 10. Unless the air is very clean the surface of the wire soon loses its brightness, and the emissivity rises, making the pyrometer less efficient. It cannot be expected that a pyrometer with a bare thermocouple will prove satisfactory in open-hearth furnace applications except for brief periods of operation when such a pyrometer may be used as a standard.

So far only simple concentric radiation shields have been considered. It is often an advantage to use more complex systems; if a sufficient number of fins is fitted to each cylindrical shield the convective heat transfer is improved and each finned shield may be equivalent to 1½ simple shields. With metal shields care must be taken to avoid thermal contact between successive shields when fins are used. Schack[3] showed that a ring of small refractory tubes formed a very efficient radiation shield, and it can be shown that each ring of small tubes may be equivalent to at least two simple radiation shields as long as the gas can pass freely all round the small tubes. The high thermal conductivity of metals makes this system unsatisfactory in metal. Extruded refractory radiation shields of special section have been most satisfactory.

Table II

EFFECT OF USING GAS VELOCITIES OTHER THAN 500 ft/s IN SUCTION PYROMETERS WITH MULTIPLE RADIATION SHIELDS

Velocity, ft/s	10	20	50	100	200	300	400	500	600	700
Equivalent number of shields at 500ft/s	0·21	0·28	0·40	0·52	0·69	0·82	0·93	1·00	1·07	1·14

Mayorcas and Burton[4] have found that a multiple refractory radiation shield enclosed in a water-cooled jacket provides an excellent means of measuring the temperature of preheated air in an open-hearth furnace. The primary advantage of enclosing the refractory system in a water-cooled housing is that it protects the outer surface of the refractory, which otherwise becomes very hot, and may be attacked by drips from the roof or by slag particles during the waste-gas part of the cycle.

It is evident from the limited number of tests carried out so far that this design of pyrometer has great possibilites, especially in the measurement of preheated air temperatures. The extruded hood illustrated in Fig. 3 has given results which seem to be accurate and dependable. Further experiments are being made by B.I.S.R.A. to determine whether an extra radiation shield might be desirable at temperatures approaching 1400° C. (An account of this work is to be published.) It should be noted that Tables I and II cannot be applied directly to pyrometers of this type.

When the radiation shield system is enclosed in a water-cooled jacket, the temperature of the surroundings differs far more from the temperature of the gas than it would if the radiation shields were exposed in the uptake. It might be inferred that the pyrometer would operate much less accurately with the radiation shields in the water-cooled housing but this is not so. Experiments confirm that the lower average temperature of the refractory radiation shields compensates for the larger temperature difference between gas and surroundings, and it is found in practice that the same radiation shield operates with about the same accuracy whether it is enclosed in a water jacket or exposed to the hot surroundings in an uptake. When the radiation shield system is withdrawn into the water jacket its life is greatly extended and the instrument becomes far more robust and reliable.

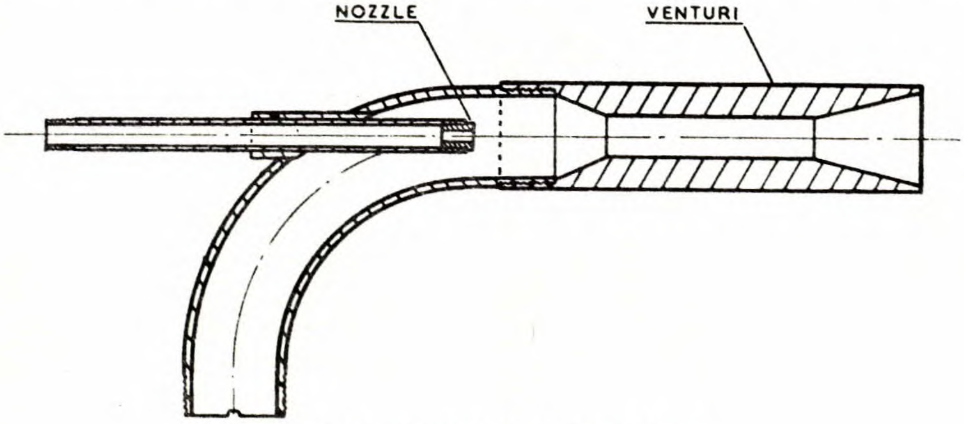

Fig. 4—Compressed air or steam ejector

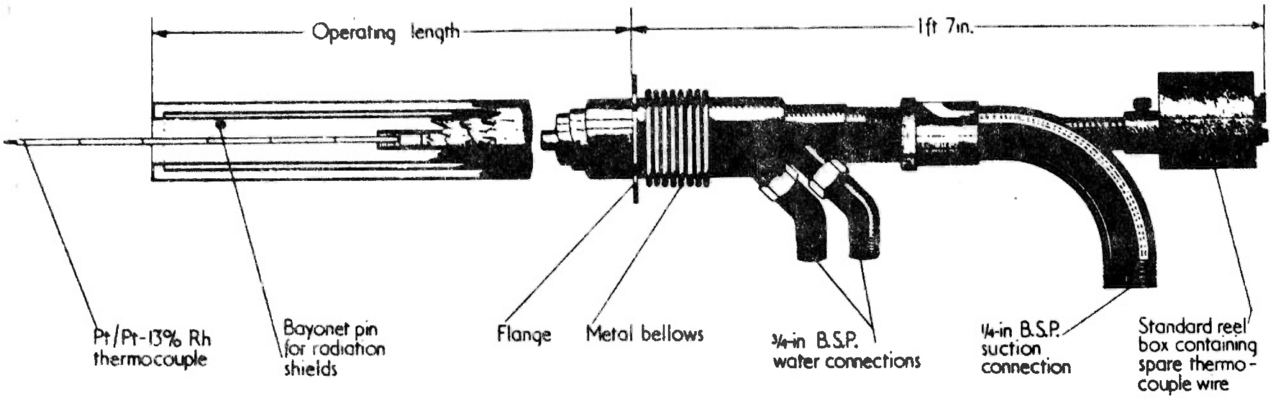

Fig. 5—Type 4 suction pyrometer

GAS VELOCITY

It has been pointed out that a high gas velocity is necessary if the suction pyrometer is to operate efficiently, but there is a limit to the velocity which should be used. When slowly moving gas is accelerated to a high velocity its kinetic energy is obtained at the expense of its thermal energy and the gas is cooled. When the moving gas comes in contact with the thermocouple tube it gives up part of its kinetic energy on impact, but a certain degree of cooling still remains. The error introduced in this way becomes of practical significance at velocities around 700 ft/s and it is unwise to use velocities much greater than 500 ft/s.

Fortunately, the theoretically desirable limit of velocity cannot be exceeded easily with the types of fans and ejectors usually available. To obtain a velocity of 500 ft/s through the radiation shield system great care must be taken with the design of the whole pyrometer, avoiding all restrictions and sharp bends. The gas should be led away in straight or gently curving pipes of adequate diameter. In some applications a fan is most convenient as only electric power is required. The gas must be adequately cooled before it reaches the fan, and this is done by providing a water-cooled section in the pyrometer. As a rough guide, it may be said that a water-cooled tube a hundred diameters long should be adequate to cool the gas from 1000° C.

In many industrial applications compressed air or steam is readily available and in such cases an ejector is a convenient means of aspirating the gases. Some ejectors described in the literature require the gas to pass round sharp bends. It has been found more efficient, and incidentally much less noisy, to use a more ‘ streamline ’ construction such as that in Fig. 4.

It is better to measure the mass flow of gas rather than the suction; it is then possible to deduce the velocity of the hot gases in the radiation shield system. The flow of the gas can be determined conveniently by using a Venturi and differential pressure meter. If the gas flow in pounds per hour is divided by the cross-sectional area of the radiation shield system in square inches, then the velocity of the hot gas may be found at once by referring to Table III.

RECOMMENDED PYROMETER

The various features of design which have been discussed can now be assembled. They are incorporated in a pyrometer, now commercially available, which was designed for use in power stations, steel-melting and other large furnaces, and glass tanks. The pyrometer (*see* Fig. 5) can be used with the radiation shields either fitted externally in the conventional manner or enclosed in the water jacket. It comprises a water-cooled probe of stainless steel usually 6 ft long, to which can be attached standard elements, such as a Venturi and meter to measure the flow of gas and either an ejector of the design shown in Fig. 4 or a fan. The thermocouple is of platinum and platinum–13% rhodium wires with a reserve of wire retained in a reel box of the type widely used in liquid steel immersion pyrometers. Either a finned Inconel sheath or a refractory sheath may be fitted to cover the portion of the thermocouple within the radiation shield system. The radiation shield is attached to the water-cooled probe by means of an internal bayonet fitting and three types of shield can be used. A shield consisting of four finned Inconel tubes is used for temperatures up to 1150° C. For temperature measurement of preheated air in the uptakes of open-hearth furnaces a special extruded refractory hood (Fig. 3) has been designed to fit inside the water-cooled probe. For some high-temperature applications a double refractory radiation shield outside the water-cooled probe is most suitable and this can be fitted when required; alternatively, the extruded hood can be used externally. The features of the pyrometer are its adaptability to

Table III

MASS FLOW OF AIR, lb/h per in²

Temp., °C	Velocity, ft/s								
	100	200	300	400	500	600	700	800	900
200	116	232	348	464	580	696	812	928	1043
400	84	168	252	335	419	503	587	670	755
600	63	126	188	251	314	377	440	502	565
800	51	102	153	204	255	306	357	408	460
1000	43	86	129	172	215	258	301	344	387
1200	37	74	112	149	186	223	260	298	335
1400	33	66	98	131	164	197	230	262	295
1600	29	59	88	117	146	176	205	234	264

a wide variety of conditions, the ease with which the radiation shield can be renewed, and the streamlined layout of the gas flow system which allows a high gas velocity to be attained.

ESTIMATING ACCURACY IN USE

When a suction pyrometer has been made and put into operation it is important to find out how accurately it is measuring the true temperature of the gas. The usual method is to take readings over a wide range of velocities and to plot a curve relating the indicated temperature to either gas velocity or suction. If the curve appears to flatten off at the operating velocity, the pyrometer is considered to be operating efficiently. In this simple form the test is of a qualitative character, but we have shown in our mathematical analysis of the problem that the shape of the temperature velocity curve can be used in a quantitative way to assess the accuracy of the readings obtained. We have also been able to indicate another way of estimating the accuracy of readings. The suction is turned on and the pyrometer is left to record the temperature until a steady value is obtained; the suction is then turned off and a second curve is recorded. The ratio of the time constants of the heating and cooling curves obtained in this way gives a quantitative estimate of the accuracy of the pyrometer.

In the most careful work on pyrometers using radiation shields fitted outside the water jacket this type of method is recommended, but there is a simple test which is adequate for many purposes. In an efficiently designed suction pyrometer the error of measurement happens to be approximately inversely proportional to the gas velocity over the higher range of velocities. The following procedure is therefore recommended. The suction is turned full on when the pyrometer is in its opening position, and the drop in temperature is noted; the velocity is then reduced by half and the temperature is observed. If the pyrometer is operating accurately, the drop in temperature when full suction is applied will be at least ten times as great as the rise in temperature when the gas velocity is halved; and this rise in temperature will be approximately equal to the error of the pyrometer operating at maximum velocity. If the ratio is much less than ten then the error will exceed the rise in temperature and may exceed it by a large factor if the ratio is less than seven. When the suction is turned off, the outlet from the pyrometer must be efficiently stopped up, otherwise hot gas or cold air may be drawn through the radiation shields by the positive or negative pressure in the furnace, relative to the atmosphere, thus giving misleading readings.

In preheated air measurement in the open-hearth furnace the drop in temperature when the suction is turned on will usually average between 100° and 250° C. We may therefore say simply that the pyrometer is operating accurately if the temperature rises by no more than 10° C when the gas velocity is halved. If the air preheat is unusually high, Cashmore[6] has shown that the temperature drop when the suction is turned on may be as little as 50° C; it is then advisable to insist that the temperature should not rise by more than 5° C when the gas velocity is halved.

The type of pyrometer in which the radiation shields are enclosed in the water jacket seems likely to be widely used. The same method of testing is recommended as the best available; the gas velocity should be halved and the change in reading will give a good estimate of the error at full velocity.

CONCLUSIONS

A suction pyrometer needs careful design and intelligent use. It is essential to provide an adequate number of radiation shields around the thermocouple, and a pyrometer with a single radiation shield is quite useless at 1000° C. In the uptake of an open-hearth furnace, a pyrometer with five metal radiation shields or three refractory shields will give accurate readings, but both may suffer from overheating or slag attack during the waste-gas cycle. The best solution appears to be the use of an extruded refractory hood in a water-cooled jacket, as proposed by Mayorcas and Burton. A rigorous method of checking the pyrometer in use is necessary and the simple method described should be adequate and convenient for routine work. If these precautions are observed, suction pyrometers can be used with confidence in any steelworks.

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