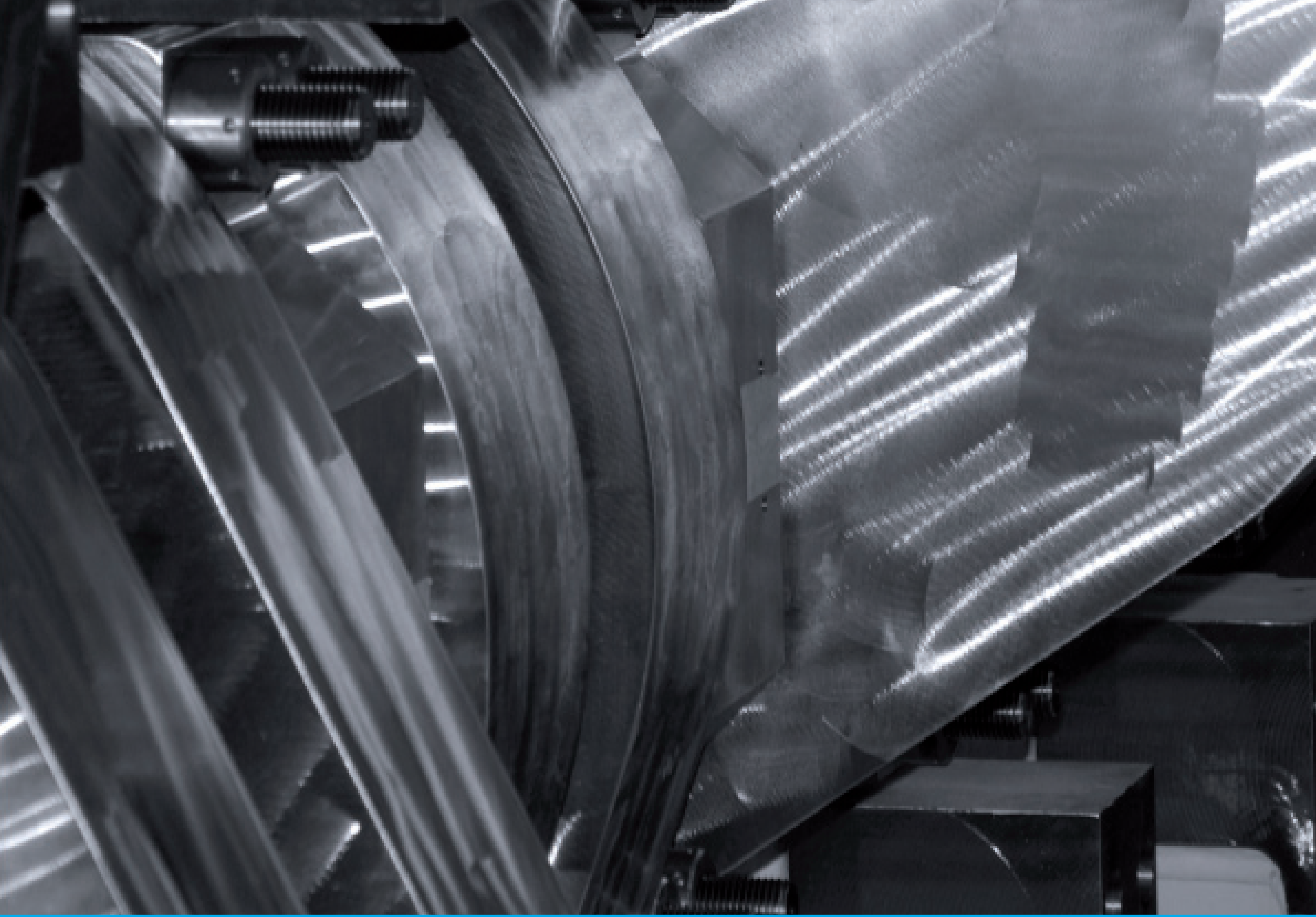
MAN Diesel & Turbo
Teglholmsgade 41
2450 Copenhagen SV, Denmark
Phone +45 33 85 11 00
Fax +45 33 85 10 30
info-cph@mandieselturbo.com
www.mandieselturbo.com



Soot Deposits and Fires in Exhaust gas Boilers

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Content

Soot Deposits and Fires in Exhaust Gas Boilers

Introduction

The demand for the highest possible overall fuel efficiency is reflected in developments in the propulsion market for oceangoing ships. Today, this market is dominated by highly efficient two-stroke low speed diesel engines which run on low quality fuels and utilise (recover) the exhaust gas heat by means of an exhaust gas boiler/economiser.

The development of high efficiency engines has resulted in reduced specific fuel oil consumption, i.e. increased thermal efficiency of the diesel engine, and thereby lower exhaust gas temperatures. Based on ISO ambient reference conditions (25°C air and 25°C cooling water), and with the present nominal ratings of the MC/MC-C and ME/ME-C/ME-B engines, the exhaust gas temperature after the turbocharger for standard engines without waste heat recovery system, is about 240-270°C, but may be lower for derated engines.

The name “exhaust gas economiser” is often used for an exhaust gas boiler which is not able to operate separately, i.e. without its own steam drum. In this paper, the name “exhaust gas boiler” will be used in general, also in cases where “exhaust gas economiser”, in principle, should have been used.

Rise in soot fire incidents

As a consequence of the lower exhaust gas temperatures and the remaining steam consumption requirements, the exhaust gas boiler has been designed to become more and more efficient. This involves the use of a large heat transfer surface and thus a boiler design with a low internal gas velocity as well as tubes with “extended” surfaces. Furthermore, the quality of the fuels has decreased significantly over time. Whereas the average fuel quality may not have deteriorated as much as predicted, single deliveries have shown exceedings of the normal data as a result of a more efficient refinery process. The residual fuel oils available on the market today contain considerably higher quantities of asphalt, carbon and sulphur that contaminate the exhaust gas and thereby increase the risk of soot deposits on the exhaust gas boiler tubes.

Some years ago, and possibly as a consequence of both the deteriorated fuel

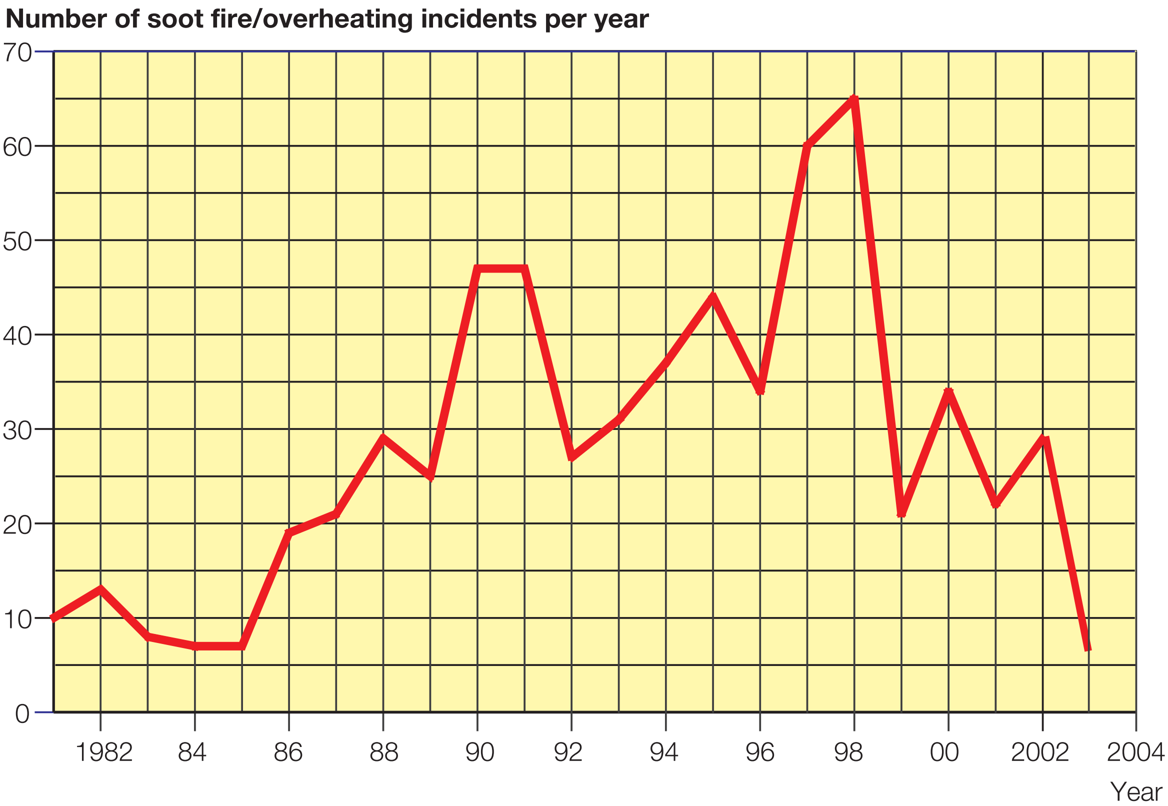

Fig. 1: Number of soot fire-damaged exhaust gas boilers in DNV-classed vessels (ref. about 5,000 vessels)

quality and the above highly efficient and perhaps "overstretched" design, it also seemed that the tendency to fouling, i.e. soot deposits on the exhaust gas boiler tubes, had increased and, in some cases, had resulted in soot fires. In extreme cases, the soot fire had developed into a high temperature iron fire in which the boiler itself burned. The above-mentioned tendency was confirmed by DNV's statistics, which reveal a sudden rise in soot fire incidents since 1985, see Fig. 1 and Ref. [1], a rise, which may also have been caused by slow steaming of ships due to the low freight rates at that time.

Since 1998, we have again seen a fall in the number of incidents, probably caused by the effect of the new recommended exhaust gas boiler design criteria introduced in the 1990s, and described in this paper.

Because of underreporting, statistics on exhaust gas boiler fire/overheating incidents after 2003 have not been worked out. Thus, whilst insurance statistics for a certain period showed 0.58 damage per ship per year, a DNV statistic for the same period revealed only 0.15 damage per ship per year. The lower number of damage reported to DNV is probably caused by more insurances with hull and machinery deductibles.

The introduction of the electronically controlled ME engine may also have had a positive influence on the reduction of the fire incidents. Thus, on a mechanically controlled MC engine the fuel injection pressure follows the engine load, whereas for an ME engine, the fuel injection pressure is more or less independent of the load, i.e. high at all loads. Hence, a better combustion, especially at lower loads, and correspondingly less soot will be the result for ME engine types. Futhermore, the introduction of the slide fuel valves of the main engines may have had a positive influence on the reduction of fire incidents, together with the introduction of the Alpha lubricator.

It is evident that the high fuel efficiency target must be met without jeopardising the reliability of the ship. It is therefore important to know the main reasons for the occurrence of soot deposits and fires in order to take the proper countermeasures against them with a correct exhaust gas boiler/system design, etc.

Warning triangle – risk of soot fire

When soot fires occur, the diesel engine will normally be blamed since the soot particles in fact originate from the engine's fuel combustion. As, in principle, particles in the exhaust gases are unavoidable from a modern diesel engine running on heavy fuel, Ref. [1], the causes of soot deposits/fires may be approached by asking a different question: What makes the soot particles deposit and/or what causes the ignition of the soot deposits?

The answer to this question may be illustrated by the "warning triangle" in Fig. 2 showing the three determining factors to be met for a soot fire: soot deposits, oxygen and ignition. As the exhaust gas smoke from a diesel engine, due to its high air excess ratio, contains about 14% oxygen, the soot deposits and ignition items are of particular interest, as the oxygen cannot be removed.

Scope of this paper

This paper is divided into two chapters which, in principle, may be considered as two separate papers.

The intention with Chapter I is to give a quick introduction to the most commonly used exhaust gas boiler types, steam systems and relevant parameters. This chapter will form a good introduction before proceeding to the issues of principle discussed in Chapter II.

Chapter II deals with the essential conditions causing soot deposits and fires in exhaust gas boilers. The reasons for soot deposits and their ignition are identified on the basis of statistical material, etc. In this context, recommendations are given which are relevant to the design and operation of exhaust gas systems and boilers.

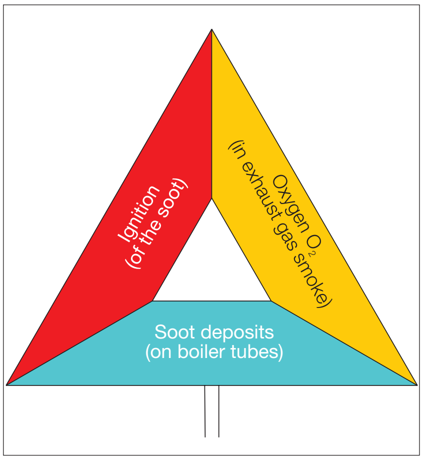

Fig. 2: Warning triangle - risk of soot fire

Basic Information and Boiler Definitions

Heat balance of a main engine

Studying a heat balance diagram which, by way of example, is shown in Fig. 3 for a nominally rated highly efficient engine version 6S60MC-C7 (or 6S60ME-C7), operating on 80% SMCR (specified maximum continuous rating), the most attractive waste heat source is the exhaust gas heat. Approximately one fourth of the fuel energy comes out as exhaust gas heat.

Even though since 1980 the exhaust gas temperature has decreased about 130°C, from approx. 375°C to approx. 245°C (ISO), as a result of the obtained higher efficiency of diesel engines, exhaust gas boilers are installed on almost all merchant ships of today. However, this development has been accompanied by more trouble, as mentioned before.

Permissible exhaust gas back-pressure
The permissible gas pressure loss across the exhaust gas boiler has an important influence on the gas velocity through the boiler. Thus, if a high pressure loss is acceptable, it is possible to design the boiler with a high gas velocity, but if only a small pressure loss is permissible, the gas velocity will be low.

The permissible pressure loss across the boiler depends on the pressure losses of the total exhaust gas system after the diesel engine's turbocharger(s).

Permissible back-pressure of exhaust gas system for MC/MC-C and ME/ME-C/ME-B engines

At the SMCR of the engine, the total back-pressure in the exhaust gas system after the turbocharger, indicated by the static pressure measured as the wall pressure in the circular pipe after the turbocharger, must not exceed 350 mm WC (0.035 bar), see Fig. 4.

An increased back-pressure may involve a too high thermal loading of the engine components together with a "too sensitive" turbocharger. Furthermore, the IMO NOx compliances may be difficult to meet.

In order to have a back-pressure margin for the final system, it is recommended at the design stage that about 300 mm WC (0.030 bar) at SMCR is used initially.

The back-pressure in the exhaust gas system depends on the gas velocity, i.e. it is proportional to the square of the exhaust gas velocity, and hence to the pipe diameter to the 4th power. It is recommended not to exceed 50 m/s in the exhaust gas pipes at SMCR.

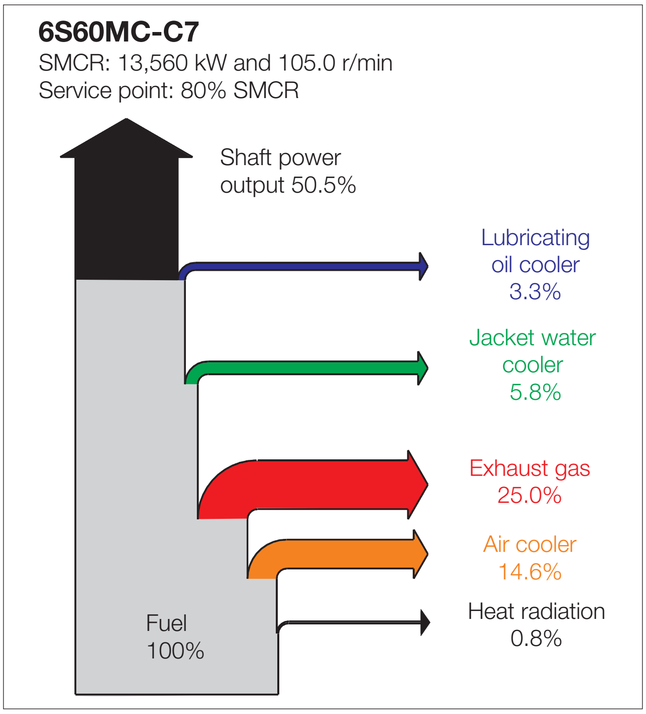

Fig. 3: Heat balance of main engine 6S60MC-C7 IMO Tier I at 80% SMCR

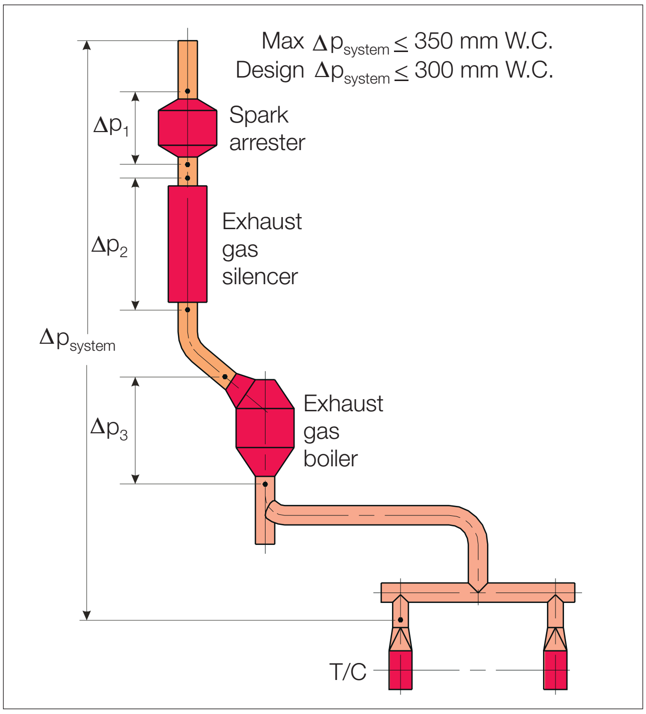

Fig. 4: Permissible exhaust gas back-pressure at 100% SMCR

It has become normal practice, in order to avoid too much pressure loss, to have an exhaust gas velocity in the pipes of about 35 m/sec at SMCR.

As long as the total back-pressure of the exhaust gas system, incorporating all resistance losses from pipes and components, complies with the above-mentioned requirements, the pressure losses across each component, such as the exhaust gas boiler and silencer, may be chosen independently.

Permissible pressure loss across boiler

At SMCR, the maximum recommended pressure loss across the exhaust gas boiler is normally 150 mm WC.

This pressure loss depends on the pressure loss in the rest of the system, as mentioned above. Therefore, if an exhaust gas silencer/spark arrester is not installed, the acceptable pressure loss across the boiler may be somewhat higher than the maximum of 150 mm WC, whereas, if an exhaust gas silencer/spark arrester is installed, it may be necessary to reduce the maximum pressure loss.

It should be noted that the above-mentioned pressure loss across the boiler also incorporates the pressure losses from the inlet and outlet transition boxes.

Boiler types

The types of exhaust gas boilers utilising the diesel engine exhaust gas heat may, in principle, be divided into two main groups:

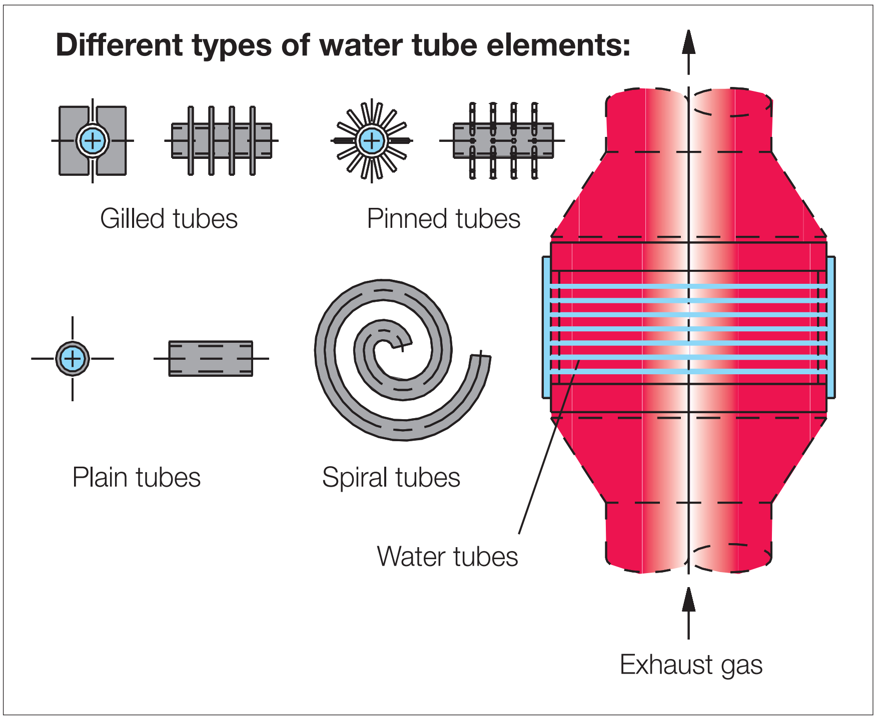

Fig. 5: Exhaust gas boiler – water tube type. The boiler shown is the vertical type without steam drum

- Water tube boilers
- Smoke tube boilers

Water tube boilers

This is the most frequently used boiler type – often in connection with high exhaust gas heat utilisation. The exhaust gas passes across the outside of the boiler tubes, with the water flowing inside, see Fig. 5. In order to make the boiler as efficient and as compact as possible, the heat transfer area on the gas side of the tubes may often be expanded with, for example, narrowly spaced, gilled (finned) or pinned tubes. The clearance between the gill-type fins (face to face) is in general 10-13 mm, and the thickness of the gills is about 2-3 mm.

The water tube boiler type will normally not be equipped with a steam space (also called steam collector or steam-

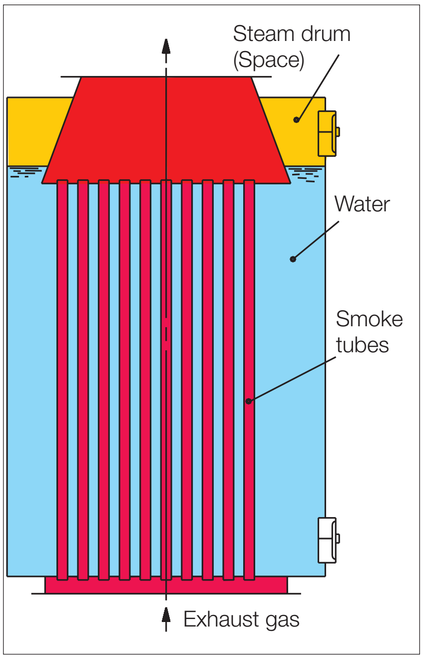

Fig. 6: Exhaust gas boiler – smoke tube type. The boiler shown is the vertical type with steam drum

drum), but will sometimes be operated in connection with a separate steam drum or, more often, with the steam drum of the oil-fired boiler.

The soot deposits on the upper side of the boiler tubes, and this type of boiler will most often be fitted with a soot-blowing arrangement in order to remove any soot deposits. The soot deposit tendency in the 1990s was on the increase due to the low gas velocity and temperature often used at that time.

In several cases, the increased occurrence of soot deposits on this type of boiler was followed by a soot fire.

In extreme cases – as mentioned later – the high temperature caused by the soot fire resulted in a so-called iron fire in which the boiler itself burned. This may have occurred due to leakage of water from the boiler because of the high temperature. The iron fire could also have occurred because the crew tried to put out the fire by activating the soot blowers for the injection of steam or water. The high temperature would thus cause dissociation of steam into oxygen and hydrogen. The oxygen may then have caused oxidation of the iron, i.e. an iron fire.

Gilled and pinned tubes are more vulnerable to soot fires than plain tubes, because the highest metal temperatures will occur on the edge of the gills, which will thus be the most likely starting point for an iron fire.

Smoke tube boilers

In smoke tube boilers, the gas is conducted through a bundle of tubes with small internal diameters (of the magnitude of 30-100 mm) and surrounded on the outside by water, see Fig. 6. The smoke tube boiler type is often chosen in specific cases where it is desirable to operate the exhaust gas boiler independently of the oil-fired boiler. This is possible as the smoke tube boiler may be fitted with its own separate steam drum.

In general, a high gas velocity in the boiler tubes is desirable in order to achieve the highest possible heat transfer and the lowest possible soot deposits.

As a cleaning system is very difficult to install, this boiler type is designed to have a self-cleaning effect, which is obtained by using a relatively high design mean gas velocity, exceeding some 20 m/s, through the tubes.

In some cases soot has blocked some of the boiler tubes, with a consequent increase in pressure loss and reduction in boiler efficiency. The solution may be to clean the tubes manually at regular intervals, although this may be expensive.

On the other hand, soot deposits have very seldom led to damage caused by soot fire, because the boiler tubes are surrounded/cooled by water and the heat surface has a limited area.

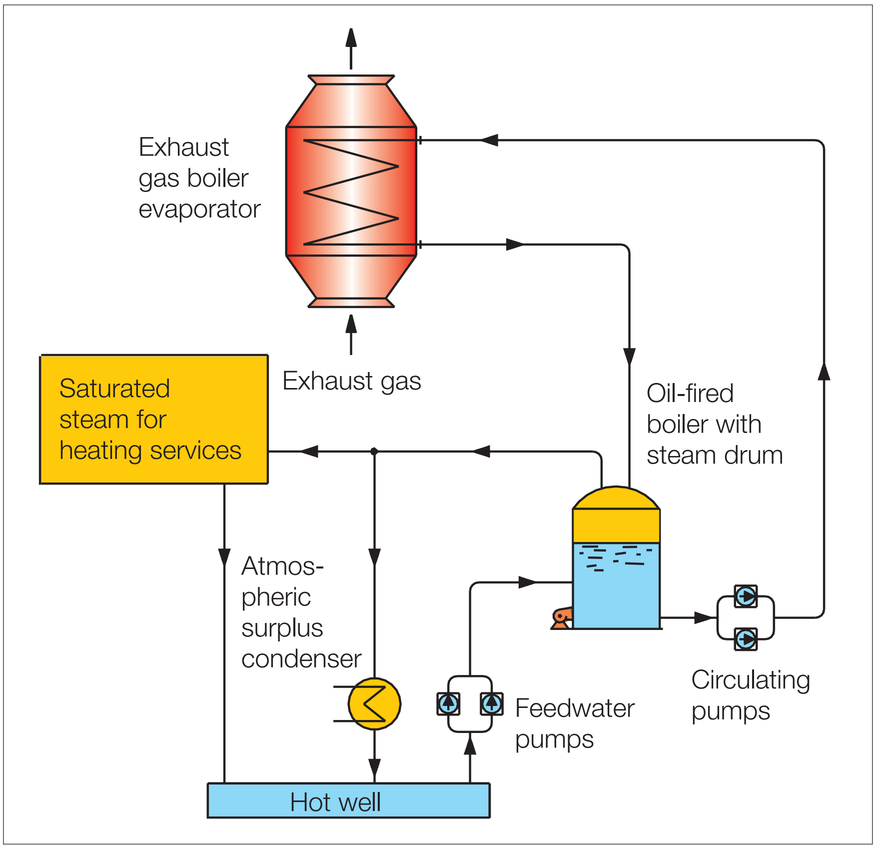

Fig. 7: Normal exhaust gas boiler system for steam production.
Single pressure steam system with evaporator section only

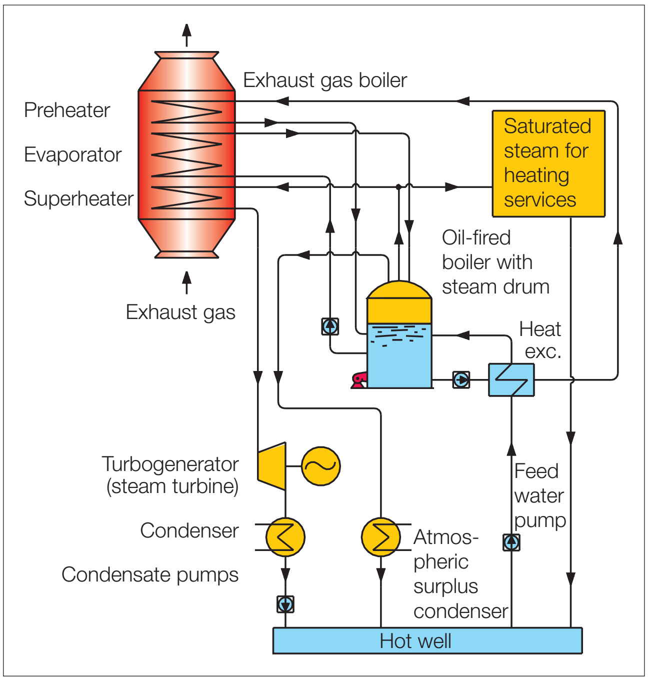

Fig. 8: Special exhaust gas boiler system with turbo generator for electricity production. Single pressure steam system with preheater, evaporator and superheater sections

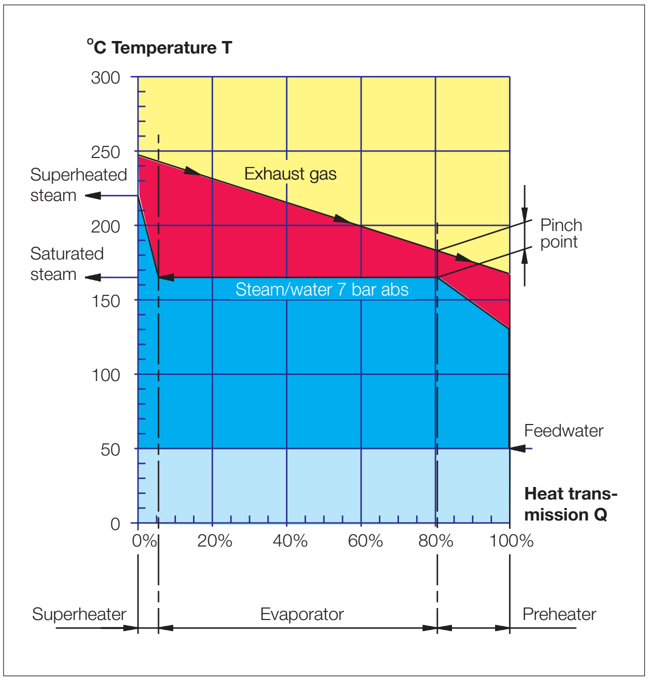

Fig. 9: T/Q diagram for an exhaust gas boiler

Boiler steam systems

Exhaust gas boiler steam systems can be designed in many different versions, with one or two pressure levels, with or without a preheater section, etc.

The most commonly used steam systems – both simple and advanced – are described below.

Normal exhaust gas boiler system

The exhaust gas boiler system normally used for the production of saturated steam needed for heating services is shown in Fig. 7.

This is a simple, single-pressure steam system in which the exhaust gas boiler consists solely of an evaporator section. The feed water is pumped directly to the oil-fired boiler which is used as a common steam drum for the oil-fired boiler and the exhaust gas boiler.

Separate steam drums may also be used, so that one boiler can be run if the other should malfunction.

Because of its simplicity and low capital cost, the above system is widely used and is often entirely adequate when the steam production is viewed as a means of meeting the steam demand for heating services on the ship.

The loss of water from the exhaust gas boiler is in the magnitude of about 1% of the steam production.

Special exhaust gas boiler system with turbogenerator

For engines with a waste heat recovery systems where a turbogenerator, i.e. a steam turbine driven electrical generator, is installed (utilising the steam available after deduction of steam for heating services), the exhaust gas boiler system will be more advanced.

A general but old example of such a system is shown in Fig. 8. The boiler is, apart from the evaporator, also fitted with a preheater and a superheater. In this system too, the steam drum of the oil-fired boiler is normally used as a common steam drum.

The influence of a boiler's pinch point

A boiler's pinch point is a parameter that can tell us a lot about the boiler's design and potential behaviour in operation. It will therefore be defined below, and its influence on some important boiler parameters will be discussed in this section.

A boiler's T/Q diagram and definition of pinch point

A temperature/heat transfer diagram, a so-called T/Q diagram, illustrates the characteristic temperature course through the exhaust gas boiler. As an example valid for the special exhaust gas boiler system shown in Fig. 8, a T/Q diagram is shown in Fig. 9.

The utilisation efficiency of an exhaust gas boiler is characterised by its pinch point. The pinch point is the lowest temperature difference between the exhaust gas and the saturated steam, i.e. the temperature difference between the exhaust gas leaving the evaporator section and the saturated steam, see the T/Q diagram in Fig. 9.

Normally, the steam pressure will be above 7 bar abs. (6 barg) and often equal to 8 bar abs. (7 barg), corresponding to a minimum evaporation temperature of 165°C. According to the T/Q diagram, the gas outlet temperature, even for a boiler with feed water preheater section, will therefore not be lower than about 165°C, when 20°C or above is used as the pinch point.

A boiler's steam production and heat transfer surface

The influence of the pinch point on the exhaust gas boiler design will be evident in the following example.

The graphs in Fig. 10 show the influence of the pinch point on the boiler's heat transfer surface and steam production, Ref. [3]. By way of example, the graphs in Fig. 10 indicate that an exhaust gas boiler with a pinch point of 5°C, compared with one with a pinch point of 15°C, will produce 10% more steam, but at the expense of having a

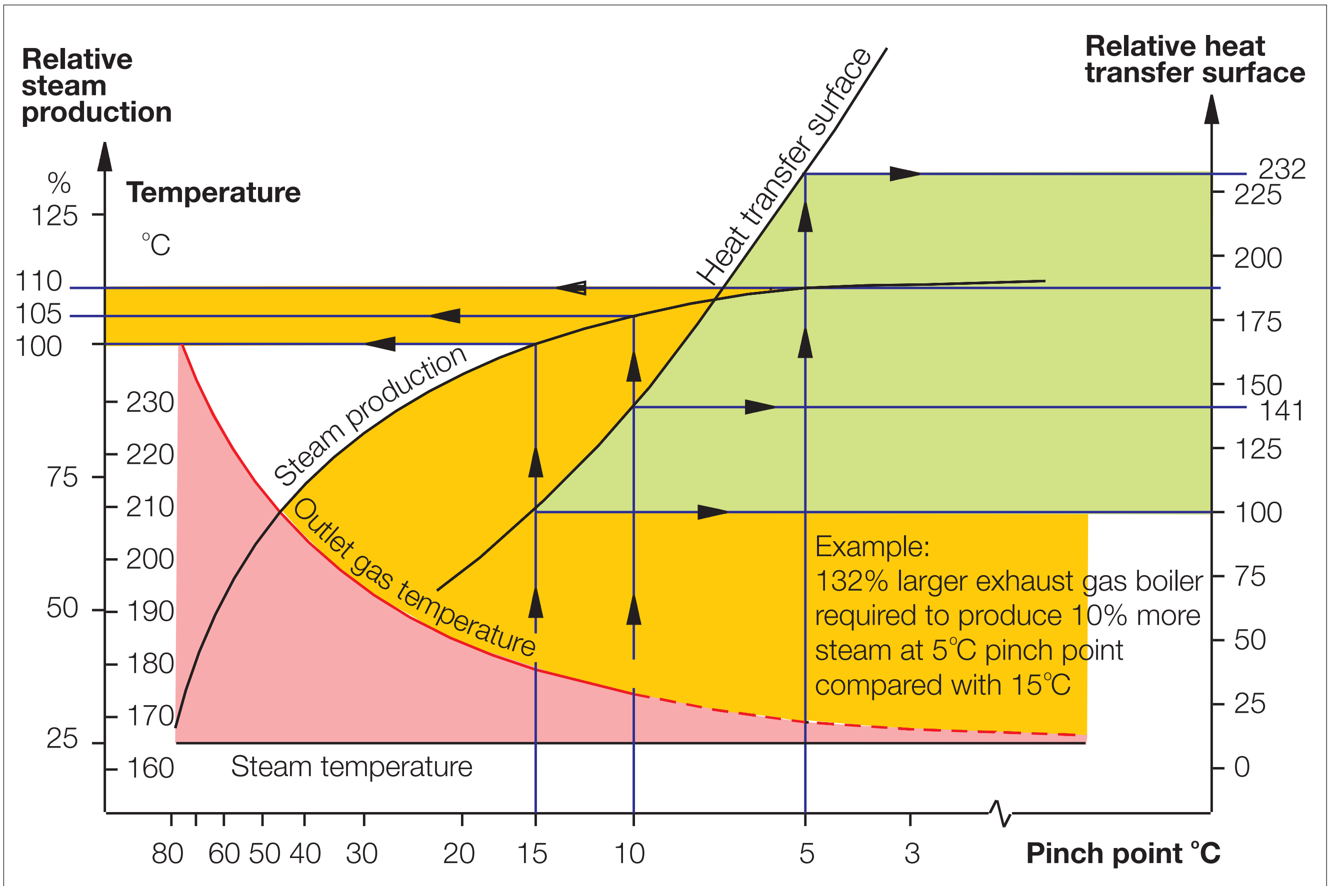

Fig. 10: Influence of a boiler´s pinch point, relative to 15oC. The graph shows the relative influence of the pinch point on an exhaust gas boiler´s heat transfer surface (size and investment) and steam production [3]

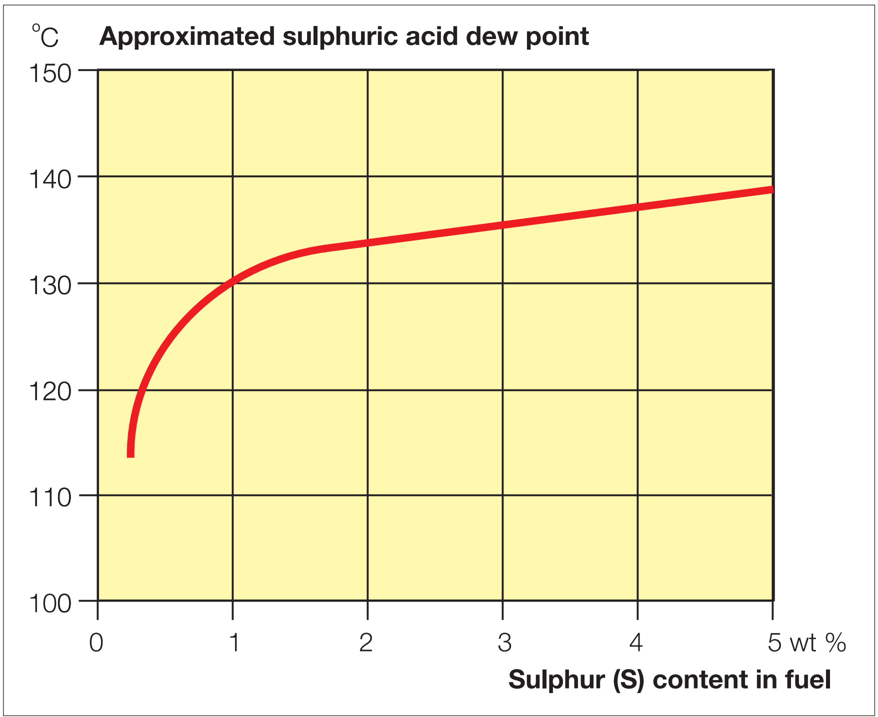

Fig. 11: Sulphuric acid dew point of exhaust gas shown as a function of the sulphur content in the fuel

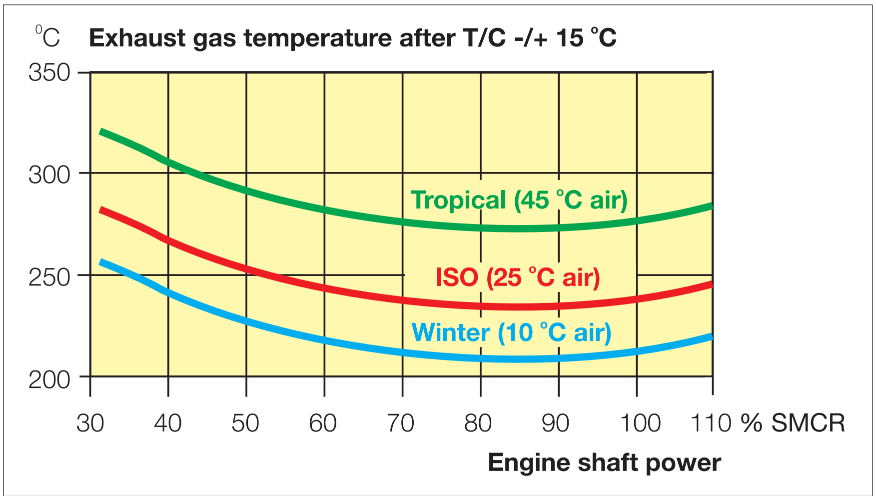

Fig. 12: Influence of ambient air temperature on the exhaust gas temperature after turbocharger for a 6S60MC-C7

heat transfer surface about 2.3 times that of the original boiler surface. The gas velocity through the boiler may be correspondingly reduced, as otherwise the pressure loss across the boiler might be too high.

A boiler´s pressure loss and gas velocity

In principle, the pinch point may be considered a measure of how extensive and how efficient the heat utilisation of the exhaust gas boiler is.

The lower the pinch point, the larger the heat transfer surfaces and the more efficient the exhaust gas boiler is, and the higher the gas pressure loss across the boiler is. As the maximum permissible gas pressure loss has a certain limitation, the boiler's design gas velocity has to be reduced in order not to exceed the limit for the permissible gas pressure loss.

This is what happened with the more efficient exhaust gas boiler design during the 1980s and 1990s because of the lower exhaust gas temperatures of diesel engines. In this context, Chapter II will show that a low gas velocity in particular will have a distinct influence on the tendency towards soot deposits, a tendency which has become worse due to the low quality residual fuels on the market today.

Low pinch point and soot deposits

The pinch point is therefore a parameter that may influence the occurrence of soot deposits when the pinch point and thus the gas velocity is low.

Conversely, a boiler designed with a high pinch point need not be a boiler with a high gas velocity. Such a boiler can, in principle, also be designed with a low gas velocity, i.e. a low gas pressure loss across the boiler.

Sulphuric acid corrosion

A high degree of utilisation of the exhaust gas heat requires the lowest possible exhaust gas boiler outlet temperature which, if the required steam pressure and thereby the evaporation temperature is sufficiently low, is limited mainly by the risk of corrosion of the exhaust gas boiler heating surfaces due to sulphuric acid condensation.

Corrosion starts when the temperature of the boiler tube surfaces is equal to, or lower than, the dew point temperature of the sulphuric acid. Furthermore, the temperature of the boiler tube surfaces (gas side) is almost equal to the water temperature in the boiler, due to the fact that the heat transfer coefficient on the gas side is extremely low compared to that on the water side.

The sulphuric acid dew point temperature depends especially on the content of sulphur in the fuel oil and of oxygen in the exhaust gas, but is rather difficult to establish.

The chemical reactions are as follows:

a. at fuel combustion:
   $S + O_2 \rightarrow SO_2$
b. at cooling of exhaust gas in the tem perature range of 560° - 200°C:
   $2SO_2 + O_2 \rightarrow 2SO_3$
c. at reaction with water:
   $SO_3 + H_2O \rightarrow H_2SO_4$

The chemical reaction b., in particular, is rather difficult to establish, the reason being that the reaction takes place rather slowly and is catalysed by soot deposits, etc., on the heating surfaces.

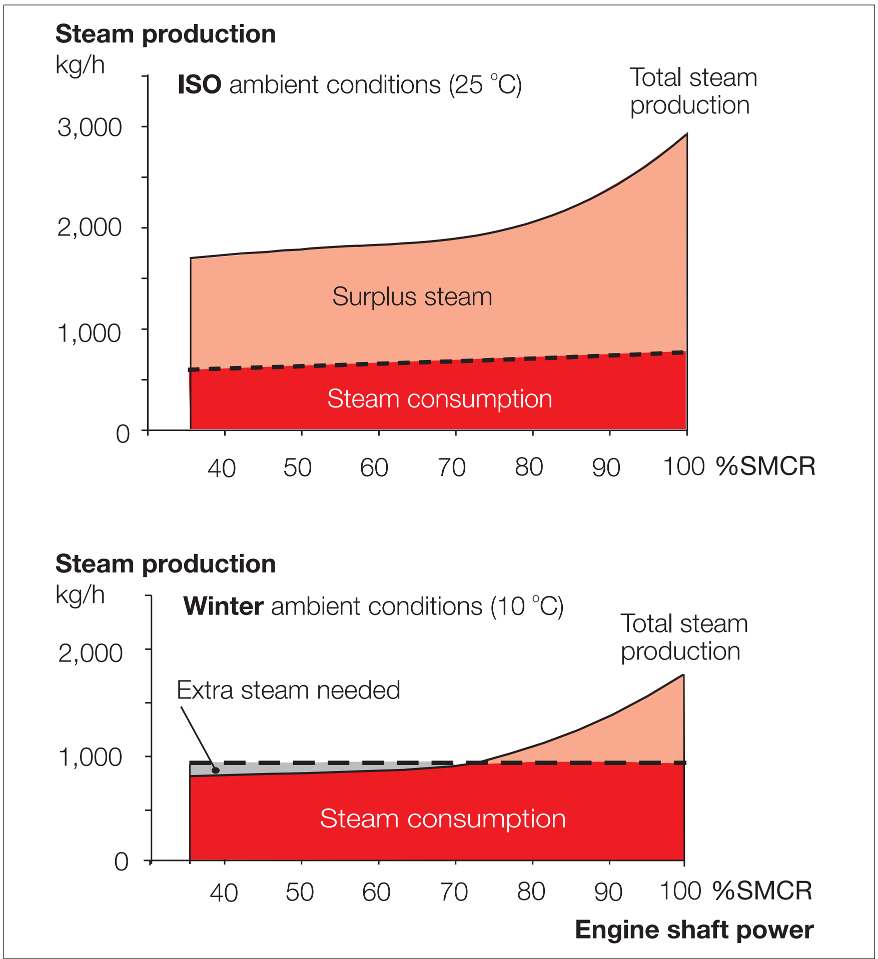

Fig. 13: Influence of ambient air temperarure on the steam production of an exhaust gas boiler installed on an Aframax tanker with main engine 6S60MC-C7

Valid for the exhaust gas after turbocharger from MC/MC-C or ME/ME-C/ME-B main engines, Fig. 11 shows, as a guide, the sulphuric acid dew point as a function of the sulphur content in the fuel. With an average 2.9% sulphur content in the fuel, the dew point of sulphuric acid in the exhaust gas from the main engine can be expected to be about 135°C, which means that in this case the temperature of boiler circulating water or feed water at the boiler inlet should be kept higher than 135°C.

Steam production – influence of ambient temperatures

During normal operation of the ship, the ambient air and seawater temperatures will change, and this will have an influence on the exhaust gas temperature. Thus, the exhaust temperature after turbochargers will decrease about 1.6°C for each 1.0°C reduction of the turbocharger intake air temperature, and vice versa.

As an example, valid for a 6S60MC-C7 engine, Fig. 12 shows the influence of the turbocharger air intake temperature on the exhaust gas temperature, valid for ISO reference conditions (25°C air/25°C c.w.), tropical air temperature of 45°C and a winter air temperature of 10°C, respectively.

A similar example (see Fig. 13) valid for an Aframax tanker having a 6S60MC-C7 main engine installed, shows the corresponding steam production of an exhaust gas boiler with an evaporator section only, and based on the steam pressure of 8 bar abs., and 20°C pinch point, together with the needed steam consumption for heating services. The upper graph for

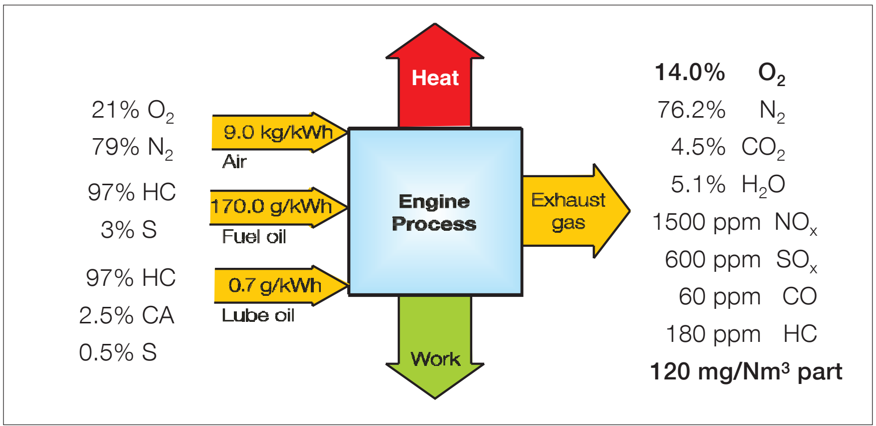

Fig. 14: Typical emissions from an MC/ME type low speed diesel engine

the ISO (25°C air) based boiler design shows that too much steam will be produced, and the surplus steam has to be dumped by means of the atmospheric surplus condenser. However, in winter time (10°C air) with a lower exhaust gas temperature, the steam production will be lower, whereas the steam consumption will increase, meaning that the oil fired boiler may occasionally have to start up to supplement the steam production.

Stage 1 Ignition of soot

Type of soot	Potential ignition temperature
Dry soot	300-400°C
Wet (oily)	150°C (120°C)

Stage 2 Small soot fires

Small soot fires are most likely to occur during manoevring/low engine load with no or limited boiler damage

Stage 3 High-temperature fires

A small soot fire may develop into a high-temperature fire with the following reactions involved:

a. Hydrogen fire, temperature > 1,000°C
Dissociation of water into hydrogen and oxygen:

$2H_2O \rightarrow 2H_2 + O_2$

} H_2 and CO are combustible

$H_2O + C \rightarrow H_2 + CO$

b. Iron fire, temperature > 1,100°C
Examples of reaction with iron:

$2Fe + O_2 \rightarrow 2FeO$ + heat

}The boiler tubes are burning

$Fe + H_2O \rightarrow FeO + H_2$ + heat

Fig. 15: Development of a soot fire in an exhaust gas boiler

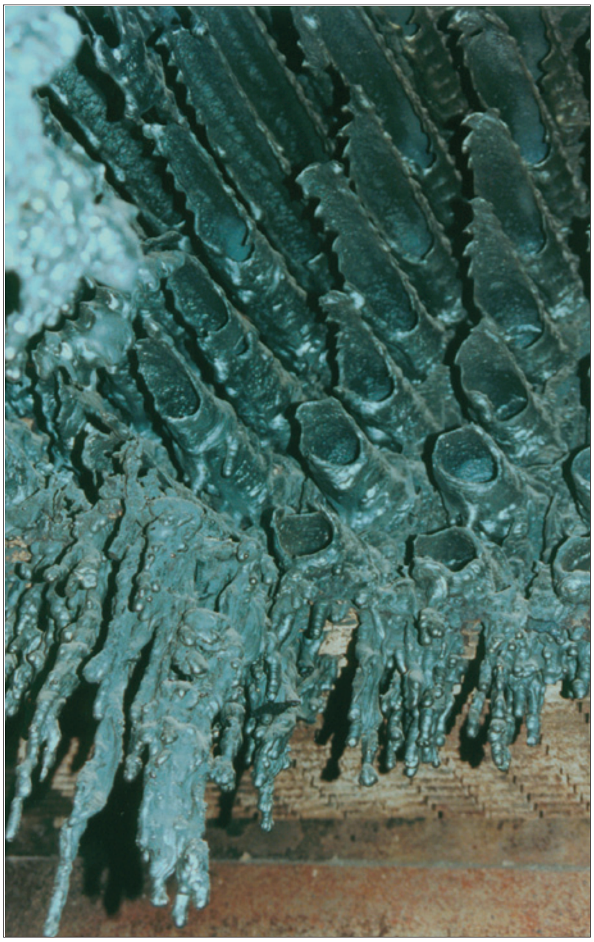

Fig. 16: High temperature fire of a gas fired water tube type boiler

Particulate emissions from diesel engines

Low speed diesels have been leading the way with regard to the acceptance of low-grade fuels, low fuel consumption and high reliability. In this process, the presence of particulates in the exhaust gas, from an operational point of view, always has been and, no doubt, always will be unavoidable.

The typical exhaust gas emission values for the most commonly discussed pollutants, NOx, SOx, CO, HC, and particulates, are shown in Fig. 14. In the context of this paper, only the particulate/soot emissions, and to some degree the hydrocarbons (HC), are of interest and will be described in the following.

Sources of particulate emissions

Particulates in the exhaust gas may originate from a number of sources:

- Agglomeration of very small particles of partly burnt fuel
- Ash content of fuel oil and cylinder lube oil
- Partly burnt lube oil
- Peeling-off of combustion chamber/exhaust system deposits.

Typical form and rate of particulate emissions

Once fuel is atomised in the combustion chamber of a diesel engine, the combustion process takes place from small droplets of fuel which evaporate, ignite, and are subsequently burnt. During this process, a minute part of the oil, comprising mainly carbon, will be left as a "nucleus".

Particulate emissions will vary substantially with the fuel oil composition and lube oil type and dosage. It is therefore difficult to state general emission rates for particulates, but when the engine is operating on heavy fuel oil, values of the order of 120-150 mg/Nm3, corresponding to some 0.8-1.0 g/kWh, may be considered typical.

In general, the particles are small and, when the engine operates on heavy fuel oil, it may be expected that over 90% will be less than 1 micron in size, excluding flakes of deposits, and peeling-off from the combustion chamber or exhaust system walls.

The particulates also include some of the ash content of the oil, i.e. the trace metals. The above-mentioned contribution from the lubricating oil consists mainly of calcium compounds, viz. sulphates and carbonates, as calcium is the main carrier of alkalinity in lube oil to neutralise sulphuric acid.

A test of the soot deposits in a boiler with gilled tubes has shown that about 70% of the soot is combustible.

Hydrocarbons

During the combustion process, a very small part of the hydrocarbons will leave the engine unburnt, and others will be formed. These are referred to as unburnt hydrocarbons, and they are normally stated in terms of equivalent methane (CH4) content.

The content of unburnt hydrocarbons in the exhaust gas from large diesel engines can be up to 300 ppm, but depends, among other factors, very much on the maintenance condition of the fuel injection system and, to some extent, on the type of fuel and the cylinder oil dosage.

The hydrocarbon figure overlaps the figure for particulates to some extent, as these consist partly of hydrocarbons.

Sticky effect of particulate emissions

If the right – or rather the wrong – conditions prevail, the soot particulates may deposit in the exhaust gas boiler. Furthermore, the lower the exhaust gas and heating surface temperatures become, the faster the soot is deposited and the harder it becomes to remove it. The explanation is that under such conditions the soot may be "wet" with oil and/or other gas condensates like hydrocarbons, and this may have an increasing effect on the tendency of soot to deposit, as the soot may be more sticky.

Soot fires in exhaust gas boilers

A fire in the exhaust gas boiler may develop in two or three stages, see Fig. 15 and Ref. [2]. The ignition of soot normally develops into a small and limited fire, but under extreme conditions it may develop into a high-temperature fire.

Ignition of soot

Ignition of soot may arise in the presence of sufficient oxygen when the deposits of combustible materials have a sufficiently high temperature (higher than the flash point) at which they will liberate sufficient vapour, which may be ignited by a spark or a flame.

The main constituent of the soot deposit is particulates but, in addition, some unburnt residues of fuel and lubricating oils may be deposited in the boiler because of faulty combustion equipment and, in particular, in connection with starting and low speed running of the engine.

The potential ignition temperature of the soot layer is normally in the region of 300-400°C, but the presence of unburnt oil may lower the ignition temperature to approx. 150°C, and under extreme conditions even down to 120°C. This means that ignition may also take place after stop of the main engine as a result of glowing particles (sparks) remaining on the boiler tubes.

Small soot fires

Small soot fires in the boiler are most likely to occur during manoeuvring with the main engine in low load operation. These fires cause no or only limited damage to the boiler, but the fires should be carefully monitored.

Heat from the fire is mainly conducted away with the circulation water and steam and with the combustion gases.
High-temperature fires

Under certain conditions, a small soot fire may develop into a high-temperature fire. Fig. 16 is an example of an exhaust gas boiler high-temperature fire, where the boiler tubes have burned and melted. The reactions involved here are (see also stage 3 in Fig.15):

A. Hydrogen fire: This occurs because dissociation of water into hydrogen and oxygen or, in connection with carbon, into carbon monoxide and hydrogen, may occur under certain conditions. A hydrogen fire may start if the temperature is above 1000°C.

B. Iron fire: An iron fire means that the oxidation of iron at high temperatures occurs at a rate sufficiently high to make the amount of heat release from the reactions sustain the process. These reactions may take place at a temperature in excess of 1100°C. In this connection, it is important to realise that also water (H_2O) may go in chemical reaction with iron (Fe), i.e. the use of the steam based soot blower will feed the fire.

Boiler Experience and Design Criteria

Statistical analyses of soot fires

Soot fires in exhaust gas boilers were very unusual before 1986, but during the period 1986-2002, soot deposits and soot fires occurred more often.

Analyses of soot fires indicate that, in most cases, they occur in connection with manoeuvring, often following a stay in harbour.

On the basis of a sample of 82 ships, most of which equipped with two-stroke main engines and water tube type boilers, the NK "Guide to Prevention of Soot Fire on Exhaust Gas Economizers 1992", Ref. [4], presented a statistical parameter survey of soot fires/overheating incidents. The survey covered 53 ships with trouble (soot fire and damage) and, for comparison purposes, also 29 NK ships with no trouble. The engines were in the power range of about 4,000-30,000 kW, and about 10% of the boilers were the large capacity types, including dual pressure type boilers.

It should be noted that the ships with trouble were extracted from a representative sample of all NK ships, while the ships with no trouble were limited to cases in which NK received answers from shipyards or boiler makers.

The parameters stated in table 1 have been obtained from the shipyards and boiler makers in question. The parameters have been studied with regard to any distinct influence on boiler trouble which can be seen in Table 1.

Parameter	Any distinct influence?	
Ship type	no	
Main engine type	no	Fig. 17
Main engine(s) MCR power	no	
Boiler sections (evaporator, preheater, etc.)	no	
Type of boiler tubes (plain, gilled, etc.)	no	Fig.18
Exhaust gas inlet/outlet temperatures	no	Fig. 19
Design mean gas velocity in exhaust gas boiler	yes	Fig. 20
Water inlet velocity to boiler	yes	Fig. 21
Circulation water flow ratio	yes	Fig. 21

Table 1: Statistical parameter survey of soot fires in exhaust gas boilers
Ref.: Nippon Kaiji Kyokai, Tokyo (NK), 1992

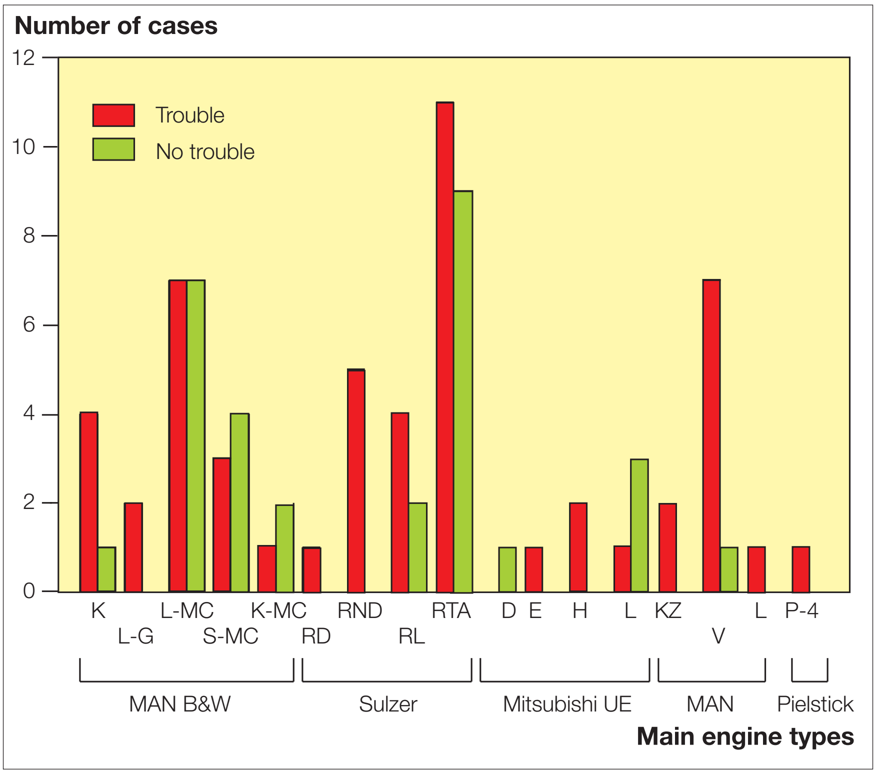

Fig. 17: Boiler trouble – influence of main engine type

Trouble/no trouble comparisons for some of the most interesting parameters have been made in graphical form and are shown in Figs. 17, 18, 19, 20 and 21.

Even though the ships included in the examination have been freely selected, for which reason simple comparisons cannot be made, the results of the comparisons may be considered very indicative.

Influence of main engine type

It is rather interesting, but not surprising, to see that the make and type of main engine had no distinct influence on the risk of soot fire, as shown in Fig. 17. Thus, the ships equipped with, for example, MAN B&W, Sulzer (Wärtsilä) or Mitsubishi two-stroke main engines, all seem to have had the same relative number of cases with and without soot fire trouble. Furthermore, statistics show that the occurrence of soot fires is also largely independent of whether it is a short or a long-stroke engine.

There is no information regarding the type of fuel oil, but, as we are dealing with two-stroke engines, heavy fuel oil has probably been used. Operating the engine on heavy residual fuels of low quality probably has an increasing effect on the tendency towards soot deposits. As low quality heavy residual fuels are cheap, this tendency may be considered as an unavoidable parameter now and in the future (unless, for example, special fuel additives are used, as indicated in recent information). Special featuresregarding “Operation on Heavy Residual Fuels” have been described in an MAN Diesel paper, Ref. [5].

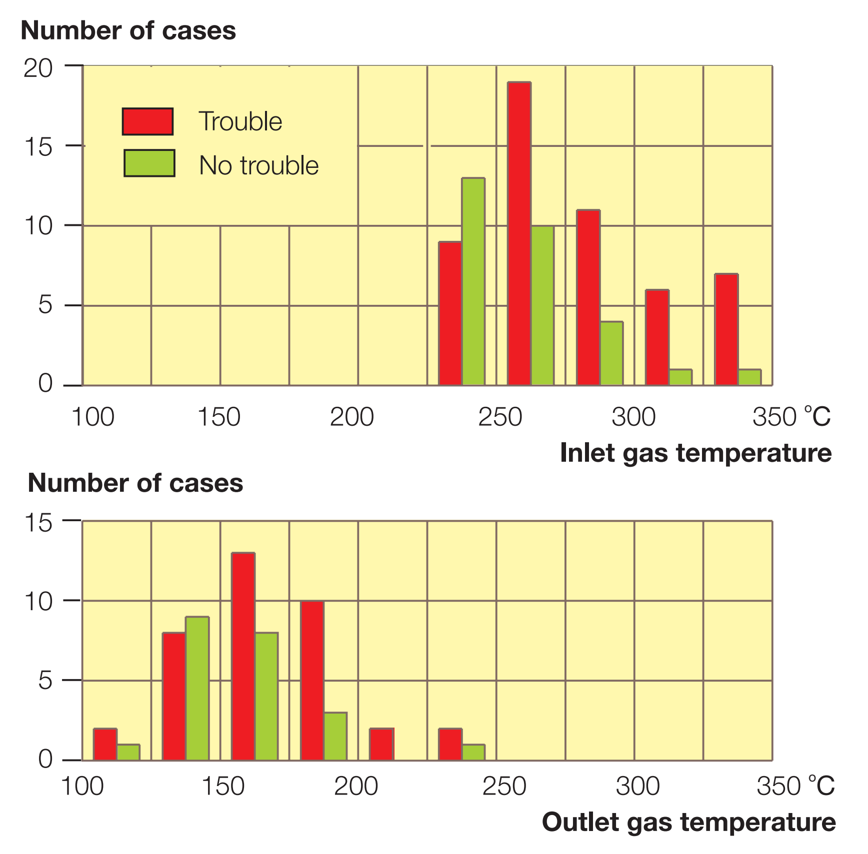

Fig. 19: Boiler trouble – influence of exhaust gas inlet and outlet temperature

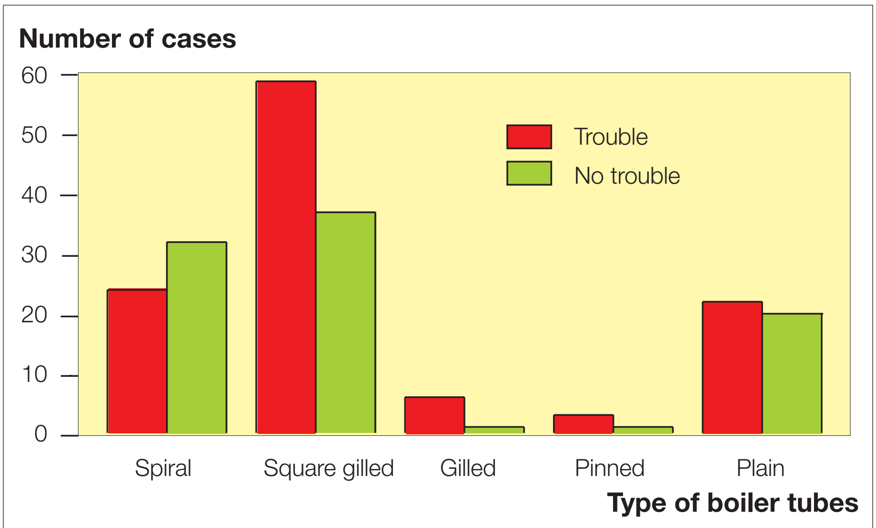

Fig. 18: Boiler trouble – influence of type of boiler tubes.
One exhaust gas boiler may count more than once as preheater sections, evaporator sections, etc. are considered as separate cases

Influence of extended tube surface

Fig. 18 shows, somewhat surprisingly, that the shape of the water tube elements used in exhaust gas boilers of the water tube type had no distinct influence on the tendency towards soot fires.

In fact, the type of boiler fitted with plain tube elements almost had the same relative number of soot fire problem as boilers fitted with tube elements with an extended surface. On the other hand, the severe cases of soot fire, with burning down of the actual tube elements,

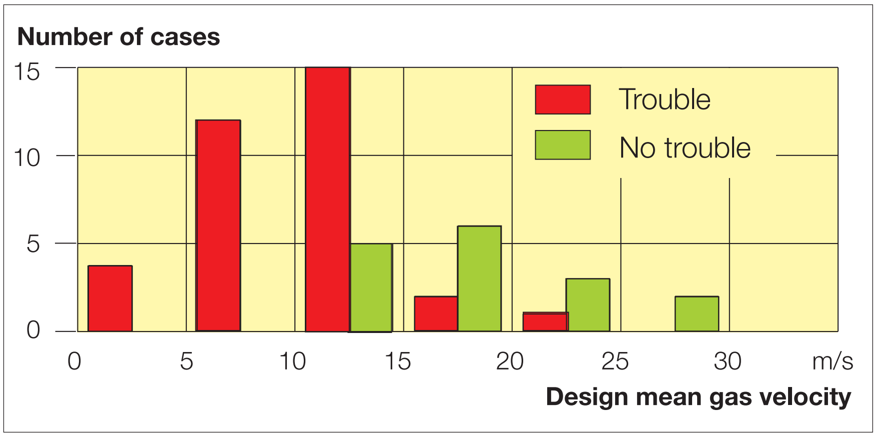

Fig. 20: Boiler trouble – influence of design mean gas velocity in exhaust gas boiler

may be more of a risk for boilers with an extended tube surface than for those with plain tubes, because the potential area is bigger, or should we say forms a reservoir for soot deposits.

Influence of exhaust gas temperature

It has often been claimed that the development of high efficiency diesel engines involving lower exhaust gas temperatures causes soot deposits in the exhaust gas boilers. However, when we only consider the influence of the actual exhaust gas temperature, statistical analyses show rather clearly that this is not correct, see Fig. 19.

Fig. 19 shows that neither the inlet nor the outlet temperature of the exhaust gas boiler has any distinct influence on the occurrence of soot fires. Even at inlet temperatures as high as 325-350°C, and outlet temperatures as high as 225-250°C, soot fires occur, and even at outlet temperatures as low as 100-150°C, many boilers had no such trouble.

The lower exhaust gas temperature can only be blamed for its possible negative influence by requiring other boiler parameters like larger heat transfer area and lower gas velocity, which can influence the occurrence of soot fires, see the next section.

Fig. 19 tells us nothing about the potential influence of the low gas temperature in the boundary layer on the cold boiler tubes. This type of low gas temperature may, despite the above results, still have an increasing effect on the tendency towards soot deposits, as the soot on the tube surfaces may be made wet and sticky by gas condensates.

Influence of low gas velocity

The statistical analyses of soot fires show, as indicated in table I, that one of the parameters that has a distinct influence is the gas velocity in the boiler, see Fig. 20.

All exhaust gas boilers based on a design gas velocity lower than 10 m/s had soot fire trouble, whereas relatively few boilers based on a design gas velocity higher than 20 m/s had such trouble.
One of the dominant parameters influencing the occurrence of soot fires, as it increases the tendency towards soot deposits, is therefore – according to the statistical material – the low gas velocity in the boiler. See also the lower side of the warning triangle in Fig. 2.

Stickiness of the soot

The low gas velocity seems to be an important factor. On the other hand, the low gas velocity limit is probably a “floating” limit which may also depend on the actual stickiness of the soot in the exhaust gas smoke, which again may depend on the actual residual fuel used (containing asphalt, carbon and sulphur).

Thus, the stickier the soot, the more easily it will stick to the boiler tubes. One could claim that the stickiness of the soot is the dominant factor for the occurrence of soot deposits.

On the other hand, Fig. 20 then shows that only the exhaust gas boiler with a low design mean gas velocity included in the statistics had exhaust gas smoke containing sticky soot, and this seems improbable.

Regarding the stickiness of the soot, information has revealed that, due to a chemical reaction with the hydrocarbons, the use of a fuel additive containing iron oxide may involve that the soot will be less sticky and more dry. The exact chemical background for this observation is not clearly understood.
The result will be a reduction in the tendency towards soot deposits because the soot is less sticky and the gas velocity limit for soot deposits will, in turn, be reduced, i.e. the soot deposits will be less sensitive to the low gas velocity

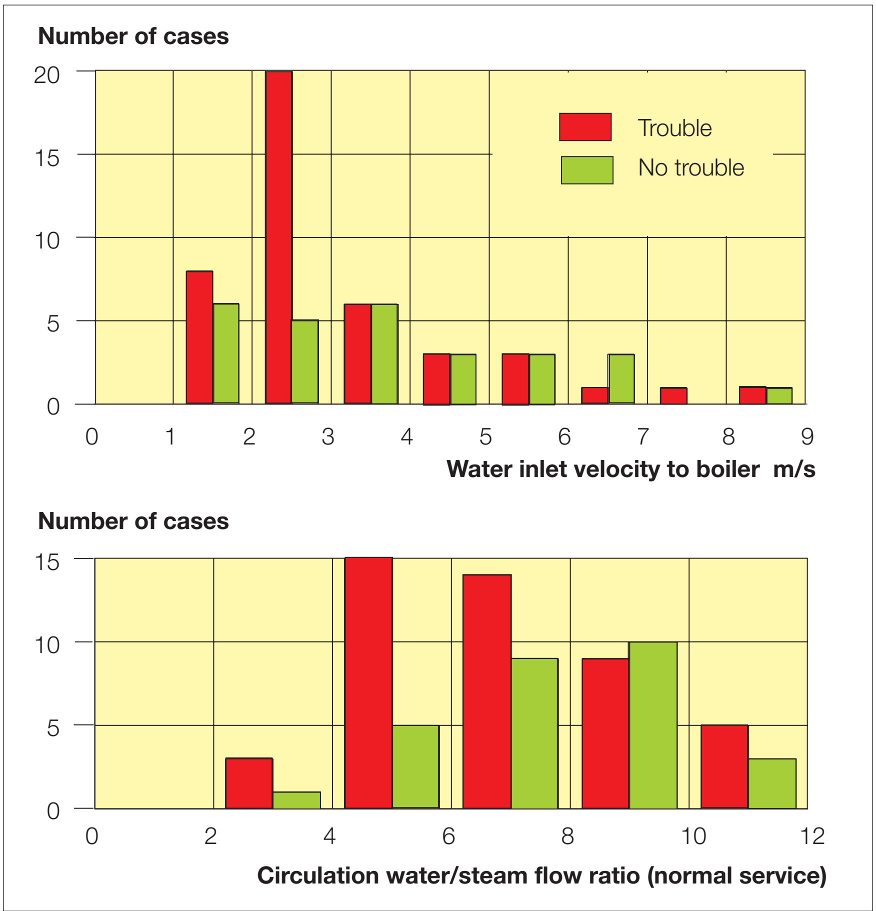

Fig. 21: Boiler trouble – influence of water circulation in water tubes

Such a fuel additive may therefore be useful in cases where the exhaust gas boilers have suffered from soot deposits

Influence of low water inlet velocity and low circulation water flow ratio

The diagrams in Fig. 21 show the influence of the water inlet velocity to the boiler and the circulation water flow ratio (circulation water and steam production mass flow ratio), and also indicate an important influence on the occurrence of soot fires.

Thus, the lower the water inlet velocity to the boiler, and the lower the circulation water ratio, the higher the likelihood of soot fire problems is.

A sufficient circulation water flow rate is therefore important to avoid critical damage to exhaust gas boilers.

This is because a low circulation water flow rate increases the risk of creating spots of steam bubbles which again involves spots with a high gas temperature on the tube surfaces, which in turn increases the risk of ignition of the soot deposits. See the upper left side of the warning triangle in Fig. 2.

When the boiler has been designed in such a way that soot deposits do not occur, there is, of course, no soot to ignite.

This may explain the trouble-free cases in Fig. 21 for boilers with a low circulation water flow rate, even though the ignition potential exists.

The impact of low gas velocities

The statistical material shows a clear tendency: when the actual gas velocity in the boiler is lower than a certain value, the soot particles in the exhaust gas will deposit on the tubes whereas, if the gas velocity is higher, the soot particles will be blown away, i.e. the boiler itself will have a self-cleaning effect. Compare the smoke tube boilers.

According to some boiler makers, the gas velocity limit for soot deposits is about 12 m/s, but may depend on the gas constituents, as discussed above. Part load running of main engine

It is important to distinguish between a boiler's design mean gas velocity and the actual gas velocity in the boiler.

When, for example, a ship is sailing with reduced speed or is manoeuvring, the diesel engine's power output, and thereby also the amount of exhaust gas, will be reduced. This means that under specific operating conditions, the actual mean gas velocity in the boiler can be lower than 50% of the boiler's design mean gas velocity.

This could explain why soot fire problems had occurred on a few boilers with a design mean gas velocity higher than 20 m/s, ref. Fig. 20, as the actual gas velocity at part load was lower than 12 m/s. A second explanation could be, as mentioned above, that the actual gas velocity limit for soot deposits was relatively high (wet soot) in the cases in question

Inlet piping to boiler

Another factor that can reduce the actual gas velocity in a specific part of the boiler is the design of the inlet piping to the boiler. It is thus not only the actual mean gas velocity through the boiler that is the decisive factor for soot deposits. It is in fact the boiler's lowest gas velocity that is decisive, as illustrated by the following example.

In one case, a smoke tube boiler suffered from soot clogging caused by a non-uniform gas flow due to a 90° bend just before the inlet to the boiler, see Fig. 22, left. Clogging with dry, hard and consistent soot only occurred in that corner of the boiler, with the low gas velocity. However, no problems were experienced on sister ships with the same main engine and boiler types with a long straight inlet pipe to the boiler, see Fig. 22, right.

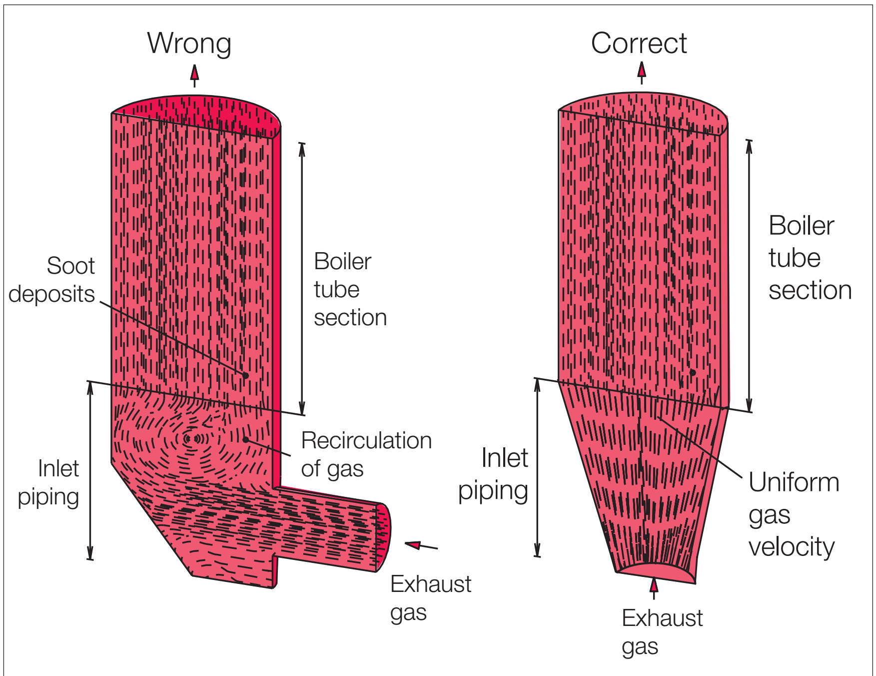

Fig. 22: Exhaust gas boiler – influence of inlet pipings

Summary of main reasons for soot fires

Given the points discussed in this paper, and with due consideration for the statistical material and the warning triangle for soot fires (Fig. 2), a general and fairly simple explanation of the main reasons for soot fires may now be given by using the analogies below.

Analogy with snow (soot deposits)

In a snowstorm at below-zero temperature, the snowflakes (dry soot particulates) will not easily deposit on the ground unless the wind (gas) velocity is reduced, as it is for example behind a fence. The low wind velocity will cause the snowflakes to deposit and form a snowdrift, and if the wind direction changes (higher velocity), part of the snowdrift may move. This means that at a certain low wind (gas) velocity, the snowflakes (dry soot particulates) will deposit.

In a thaw, for example, when the snowflakes are wet (wet soot), the snowflakes will deposit more easily, and a change in the wind direction (higher velocity) will make only a small part of the snowdrift move. Thus, the wet snowflakes (wet soot) will deposit, but will do so already at a wind velocity (gas velocity) which is higher than the wind (gas) velocity for the above-mentioned frozen snowflakes (dry soot).

In general, therefore, high wind (gas) velocities and frozen snowflakes (dry soot) will reduce the tendency towards deposits.

Analogy with coal briquettes (ignition)

Igniting a coal briquette (dry soot) for a grill is quite difficult, as its ignition temperature is rather high. On the other hand, if the briquettes have been wetted with oil (wet soot), the ignition temperature will be lower and it will be easier to ignite the briquettes (wet soot). The higher the temperature of the wetted briquettes (wet soot), the easier they are to set on fire.

So in general, the drier the briquettes (soot), and the lower the temperature, the more difficult they are to ignite.

Analogy with putting-out a fondue fire (oxygen)

If the oil in a fondue pot has become too hot and has been set on fire, the easiest way to extinguish the fire is to put a cover over the fire and stop the supply of oxygen.

When a soot fire occurs in an exhaust gas boiler, similar action has to be taken. In this case the oxygen supply is stopped by stopping the diesel engine,

as the engine's exhaust gas still contains about 14% oxygen.

General four main parameters

Given the points discussed above, the risk of soot deposits and ignition followed by soot fires may be minimised by respecting the following four main parameters – valid for both water and smoke tube boilers:

- The gas velocity in the boiler must not be too low – this reduces the main risk factor for soot deposits.
- The gas temperature on the boiler tube surfaces must not be too low – this reduces the additional risk of soot deposits due to the formation of wet soot.
- The engine smoke emission should not be allowed to deteriorate – as this will increase the tendency towards soot deposits.
- The circulation water flow velocity and ratio in the boiler must not be too low – this keeps the gas temperature at the boundary layer of the boiler tubes below the ignition temperature of the soot.

The first three of these parameters relate to the soot deposits, whereas the fourth parameter relates to the risk of ignition of the soot.

Recommended boiler design criteria

The boiler design criteria that can be recommended on the basis of the four main parameters mentioned in the above section, with due consideration for the influence of the low gas velocity, are thus as follows:

Referring to soot deposits:

A. The design mean gas velocity of the boiler should be higher than 20 m/s, but the limit may, in fact, depend on how dry and sticky the soot is (fuel type/fuel additive)

B. The pinch point temperature of the boiler should be higher than 15°C or, even better, 20°C.

C. The boiler's exhaust gas outlet temperature should not be lower than 165°C as otherwise condensation of sulphuric acid in the exhaust gas could make the soot sticky

D. The inlet piping to the boiler should be designed so that the gas flow velocity distribution is as uniform as possible, in order to avoid local points with a particularly low gas velocity.

E. The exhaust gas design pressure loss across the boiler should be as high as possible – increasing the gas velocity in the boiler. This means that the pressure losses in the remaining parts of the exhaust gas system should be dimensioned as low as possible (large pipe diameters).

F. A dumping condenser should be installed to control steam production/consumption. A gas by-pass valve installed to control the steam production will reduce the gas velocity in the boiler – and consequently increase the risk of soot deposits – and therefore cannot be recommended. The supplementary recommendations below apply only to boilers of the water tube type:

G. A by-pass duct with an automatically operated on/off valve (open/closed at approx. 40% SMCR) may in certain operating conditions be recommended, especially for water tube type boilers. If, for example, the ship is often slow steaming, i.e. the diesel engine operates at low load, such an installation will prevent soot deposits on the boiler tubes by by-passing all the gas and thereby avoiding low gas velocities and the associated risk of soot deposits in the boiler.

H. Automatic soot blowers for frequent cleaning should be installed in water tube boilers in order to clean the tubes of soot. The pressure of the soot blowing medium should be as high as possible during the entire soot blowing sequence. As the possible steam pressure used is only about 7 barg, and in some cases 6 barg, the use of high-pressure air will be better.

I. Fixed water washing system and/or manual cleaning at regular intervals. Water washing is performed in order to clean the boiler completely of soot which has not been cleaned away by the soot blowers. The exhaust gas piping between the engine and the boiler should be so arranged that the boiler can be cleaned more thoroughly from time to time when the engine is stopped in harbour without the risk of flooding the engine/turbochargers with cleaning fluid. Water washing should preferably be undertaken while the tubes are still hot, making it easier to remove the soot as it will "crack".

If the above-mentioned on/off exhaust bypass is installed, the boiler can be bypassed. Water washing should then also be carried out during sea service as often as possible (when the exhaust pressure loss increases), and not only during stops in harbour. After water washing, it should be checked that no soot is left, as remaining wet soot may increase the risk of soot deposits when continuing operation

J. The water circulation temperature at the boiler inlet, for boilers with a preheater section, should be higher than 140°C as otherwise too low temperatures could cause some of the gas constituents, such as fuel and lube oil vapour, to condense on the cold boiler tube surfaces, and this could increase the tendency towards soot deposits. An advantage of this is that the temperature of the preheater tube surfaces can then be higher than the dew point of the sulphuric acid in the gas, thus minimising the risk of sulphuric acid corrosion.

Referring to ignition

K. The circulation water flow velocity and ratio at the boiler inlet should be as high as possible in order to keep the gas temperature at the boiler tube surface as low as possible (in contrast to point J). The water flow ratio (water flow/steam production ratio) is recommended to be equal to or higher than 6. This should reduce the risk of ignition of possible soot deposits, which can happen at temperatures above some 150°C and, under extreme conditions, even as low as 120°C.

It is therefore also very important to ensure the best suction conditions so that cavitation does not occur in the circulating pumps under any working conditions, as otherwise the circulating water flow could be reduced or even stopped.

A temperature monitoring system mounted above the boiler might be recommendable as a means of detecting a fire in the boiler as soon as it starts.

Recommended operating conditions

In view of the damage that can be caused by an extensive soot fire in the exhaust gas boiler, it is recommended, during the operation of the ship, to give due consideration to the following:

Normal operating conditions

A. Soot-blowing. If soot-blowing equipment is installed, we recommend checking its efficiency and adjusting the number of daily soot-blowings accordingly.

B. Preheated feed water during start-up In order to avoid the condensation of some of the gas constituents, preheated feed water should always be used (temperature higher than 140°C) during start-up and during low load operation, especially if the boiler is not fitted with an on/off by-pass duct/valve which can be activated in these running conditions.

C. Water circulation, correct functioning. It should be ascertained that the boiler's water circulation system and its control system are functioning properly.

D. Water circulation after engine stop. After the engine is stopped, the boiler's water circulating pump should be kept running until the boiler temperature has fallen below 120°C, because wet oily soot may catch fire at temperatures as low as this. On the other hand, it is recommended not to stop the circulating pump in harbour unless the boiler has been checked and is clean.

E. Heavy smoke from engine. If excessive smoke is observed, either constantly or during acceleration, this is an indication of a worsening of the situation. The cause should be identified and remedied. Excessive smoke could be caused by defective fuel valves, a jiggling governor, incorrect adjustment of the governor fuel limiter, or malfunctioning of one (of two) auxiliary blowers, etc. The boiler should be checked and cleaned if necessary.

Operating conditions in water leakage situations

DNV has described a case where a water leakage was discovered from a water tube type exhaust gas boiler, Ref. [6]. In order to get to port, the water circulation was shut off. When arriving at anchorage, the exhaust gas boiler overheated, and the crew found that a high temperature soot fire had occurred.

The above case shows how important it is to cool the tubes to avoid ignition of the soot, i.e. the water circulation through the tubes must always function correctly.

In this case, the water circulation could not continue because of the water leakage. Therefore, in such a situation the below actions are recommended:

Actions to be taken prior to dry running:

A. When shutting off the water circulation, the main engine should also be shut down so that the exhaust gas boiler can cool down and any smouldering of soot deposits on the boiler tubes can die out.

B. The heating surface should be inspected carefully for soot deposits, and water washing performed, both for cleaning and cooling.

C. Make every effort to reestablish the water circulation to the boiler, thereby reducing the dry running period to a minimum.

D. Boiler manufacturers allow dry running of exhaust gas boilers only in the case of emergency and with a clean boiler. In addition, they emphasise that every possible precaution must be observed to prevent soot fire.

Actions to be taken during dry running:

E. Increase the frequency of soot blowing considerably, and perform soot blowing several times prior to manoeuvring

F. Inspect the boiler frequently and, if any soot is present, then water wash the boiler and increase the soot blowing frequency

G. The boiler instruction manual must be read carefully and its instructions are always to be followed.

Operating in soot fire situations

If a soot fire does start after all, one of the following two types of measures, depending on the level of fire, is recommended:

Fire level 1: an initial soot fire has just been discovered:

A. Stop the main engine, and thereby the oxygen supply to the fire.

B. Continue operating the water circulating pump.

C. Never use soot blowers for firefighting, as air will feed the fire with oxygen, and steam will involve a risk of high temperature fire.

D. Stop the air circulation through the engine, and thereby the air supply to the fire, i.e. keep air pressure on the diesel engine's exhaust valve closing mechanism (closed valves).

E. Use water washing, if fitted, to extinguish the fire. This is normally connected to the ship's fire fighting water system.

In a well-run plant any fire that starts will be small, and if the above emergency action is taken immediately, the fire will be damped down quickly, and water circulated by the pump will help keep the tubes cool and reduce any heat damage caused by the fire, Ref. [2].

If the soot fire has turned into an iron fire, this can be indicated by a loss of water, for example, if the feed water consumption increases very much and/or if a low level alarm in the steam drum is activated. A temperature sensor (normally max. 400°C) will not normally be able to measure the high temperatures.

Fire level 2: boiler tubes have melted down:

A. Stop the main engine, if it is not stopped already.

B. Stop the circulating water pump.

C. Close valves on the water circulation line.

D. Discharge the (remaining) water from the exhaust gas boiler sections.

E. Cool down with plenty of splash water directly on the heart of the fire.

DNV warns that, if a soot fire has turned into a high-temperature fire (hydrogen/iron fire), care should be taken when using water for extinguishing. The fire may become worse unless large amounts of water are applied directly to the heart of the fire. The main objective when

discovering an initial small fire is to prevent it from turning into a high-temperature fire.

Closing Remarks

In principle, the most efficient exhaust gas waste heat recovery system will contribute to the best overall economy on the ship provided, of course, that the recovered heat, for example in the form of steam, is needed on board the ship.

Normally, the exhaust gas boiler design will be based on a steam productionrequirement related to the rather high steam consumption needed in extreme winter conditions.

However, when a ship operates worldwide in normal trades, these winter conditions may occur only a few days a year. The choice of a smaller boiler with lower design steam production may therefore mean few disadvantages, provided the steam requirement fornormal sea service can be met.

One advantage of this will be that the design gas velocity through the smaller boiler will be higher and, as explained in this paper, this will reduce the risk of soot deposits and fires.

As an additional advantage, the exhaust gas boiler will be cheaper.

A boiler and system design based on the correct criteria will reduce the risk of soot deposits and fires in exhaust gas boilers. The use of such criteria is therefore very important and could probably be introduced with advantage into the recommendations of the Classification Societies. This would also allow boiler makers to offer boilers on equally competitive conditions (by, for example, specifying automatic soot blowers in water tube boilers).

The use of special fuel additives with iron oxide seems to reduce the stickiness of the soot and may be useful in cases where the exhaust gas boilers are vulnerable to soot deposits (for example large capacity boilers).

The statistical material from DNV (Fig. 1) shows a considerable reduction in soot fire cases from 1998 to 2003, but also indicates that great attention to installation and operation of exhaust gas boilers is still needed. Thus, great attention to operation is needed when sailing at reduced ship speeds, i.e. under low load operation of the main engine.

Reference

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