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Marine fluidised bed waste heat boiler

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Abstract

In view of highly remarkable concern about the environment protection issues nowadays, the problem of reducing the utilization of fuels and releasing the cleanest possible combustion gas has become very substantial and important point. In that aspect the designers developed a design solution of fluidised bed waste heat boiler providing remarkably high intensification of heat exchange process. The system enables to generate bigger amounts of steam than conventional utilization boiler do for the same size surface to be heated and in the same time to avoid more often the necessity to support its operation with auxiliary fired boiler. The article considers the problems arising from sulfur oxide neutralization of combustion gas released from engines when using the fluidised bed waste heat boiler. The article contains also the brief comparative analysis of conventional utilization boiler and fluidised bed waste heat boiler.

1 Introduction

A critical element of systems recovering the waste heat of marine engine combustion gas is the utilization boiler. Present conventional design solutions concerning those types of boilers, despite being energy-efficient designs indeed, have appeared to reach the limit of potential capabilities. To avoid the over-expansion in boiler heating surface size such solutions should be searched for that would enable to intensify the heat exchange process itself. The fluidised bed waste heat boilers have created the opportunity to solve the problem. The properties of fluidised bed allow to gain higher coefficients related to taking over the heat from the bed to the heated surface immersed therein than in case of taking the heat over from combustion gas to the surface heated in conventional boiler.

In power engineering applications the fluidised bed waste heat boilers are more and more often used, mainly coal fired boilers. In late 1970s, in fuel crisis period, the pioneer designs of marine fluidised bed waste heat boiler were developed. However, the first fluidised bed waste heat boiler used on the vessel was the utilization boiler. The boiler of that type was installed in 1977 on the ship "Fjordshell" with engine type Sulzer 6RND76. The said system generated up to 3855 kg/h of steam at pressure 14 bars, e.g. Cusdin [1]. Later, as the situation on the fuel market improved, the fluidised bed waste heat boilers were no longer of much interest of ship power plant designers. Nevertheless, it would be. worth reconsidering the purposefulness of use of such boilers on vessels since they could enable to reduce sulfur compound emissions. The catalysts proposed for ship engines nowadays are capable to neutralize effectively only the nitrogen oxides (SCR method) while no efficient solutions have been developed so far to remove sulfur oxides from combustion gas. The methods applied in power engineering are practically useless in case of vessels due to the large-scale of such systems.

2 Basics of fluidised bed waste heat boiler operation

2.1 Fluidization process

The design of fluidised bed waste heat boiler is based on the phenomenon of pulverized material fluidisation, i.e. the material particles are suspended in flowing gas stream. The suspension formed that way, called a fluidised bed, shows intensive motions of particles that result in excellent mixing of the bed and providing uniform temperature in its entire volume. The latter feature appears essentially effective where a boiler with such a bed is to be used as the waste heat boiler. The fluidisation process takes place in particular range of gas flow speed values. At speed values lower than the lower speed limit the gas stream is filtered by zigzagging, porous channels of stable bed and when the lower speed limit is exceeded the fluidisation starts. On the other hand, the speed values greater than upper flow speed limit cause the bed material to be whirled by gas - all resulting in transformation to pneumatic transmission phase.

The bed material may consist of burnt wood ash or other inertial material, e.g. sand, ceramic balls, aluminum granules or aluminum oxide granules. The material layer thickness in its steady state and material packing density determine the pressure loss in gas flow. Therefore, in case of utilization boiler the appropriate selection of those two parameters, i.e. material thickness and density, constitutes a fundamental determinant where the pressure loss in engine exhaust system is to be maintained within the limits specified by engine manufacturer. The test results indicate that the gas flow resistance values during its passage through the bed rise until the fuidisation phase is reached and afterwards the resistance remains nearly constant value, e.g Razumov [2].

In case of fluidisation of fine grain materials the highly efficient dust catcher systems have to be designed to reduce articles emerging out of the devices. The emerged solid fraction has to be redirected back to the bed. Moreover, to maintain the fluidisation steady state the dynamic control of fluidising agent is required.

2.2 Heat exchange process between the fluidised layer and the heating surface immersed in it

The process of transferring the heat from the fluidised layer to the heating surface in the boiler is a complex process and different from the processes in conventional boilers. The fluidised layer shows extensive turbulence both in gas and solid phase.

There are two heat exchange processes observed in the fluidised beds. The first process is the heat transfer from the gas to the bed particles, the other process is the heat transfer from the bed to the heating surface immersed in the bed. High turbulence causes the combustion gas boundary layer formed close to the heating surface to be of very slight thickness; such conditions facilitate convection heat transfer. The bed particles continuously hit the heating surface disturbing the formation of boundary layer but touching the heating surface they transfer their heat by conduction. Due to the specific bed structure and bed temperature the heat exchange by way of radiation is insignificant and accordingly, the majority of heat is transferred in the process of convection heat transfer.

The determination of heat transfer coefficient for the bed is a complex issue affected by several factors. There are numerous calculation formulas for heat transfer coefficient found in professional publications, however, none of them can be treated as a universal formula that could be applied for full range of parameter variability. The research results have proved that the coefficient of heat transfer between the bed and the surface immersed therein can reach a value up to 1000 W/m^{2}K, e.g. Wiśniewski [3]. The heating surfaces immersed in a bed are, in most cases, the bunches of horizontally running pipes. For comparison purposes, the Authors of this article have chosen the formula presented below, e.g. Wolański, Drabik [4].

$$\alpha_{fr} = 353{,}817 - \frac{183{,}622}{N_F} - \frac{176{,}209}{\frac{l_{poz}}{d_z}} - \frac{18{,}246}{\frac{l_{pion}}{d_z}} \left[\frac{W}{m^2 K}\right] \qquad (1)$$

where:

N_F – fluidisation number

l_{poz}, l_{pion} – horizontal and vertical bunch of pipes immersed in the bed

d_z – external diameter of a pipe in the bunch

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2.3 Desulfurization of combustion gas

One of the main advantages of a fluidised bed is its capability to remove sulfur compounds from combustion gas directly in the bed. That feature enables the sulfurised fuels to be safely burned, satisfying the environment protection requirements, and without costly investments in construction of separate desulfurization plants.

The sulfur sorbent can be transferred to the bed by means of pipes with holes arranged appropriately along the pipe perimeter providing pneumatic transmission. The capability of dry desulfurization of combustion gas by means of adding a sorbent directly to the fluidised bed constitutes one of the most significant advantages of the fluidised bed waste heat boilers. In case of fired boilers the most often used sorbents are lime stone $CaCO_3$, dolomite, hydrated lime or carbide lime residues. Due to relatively low temperature of combustion gas the primary sorbent applicable for fluidised bed waste heat boiler is pure CaO. The following reactions in the bed can be observed:

$$CaO + SO_2 \Rightarrow CaSO_3 + \text{heat energy}$$

$$CaO + SO_2 + \tfrac{1}{2}\, O_2 \Rightarrow CaSO_4 + \text{heat energy}$$

The desulfurisation effectiveness is determined with molar ratio Ca/S (equal to 2-4,5) and the contact time between the sorbent and combustion gas (should equal to approx. 0,5 sec) and the sorbent grain size. The stoichiometric demand for CaO required to obtain the total fuel sulfur volume bonded equals to approx. 1,75 kg of CaO per 1 kg of S, e.g. Nowak [5]. The sorbent grain size should be correspondingly small to enable the removal of reaction products from the bed by way of blowing them out with combustion gas flux.

An essential problem in case of a waste heat boiler is the relatively small height of its bed, enforcing the sorbent grains to stay in the bed for a short time. The latter conjoined with the low combustion gas temperature may essentially affect the desulfurisation effectiveness. Moreover, the system would require to install the cyclone separator or other similar system to enable the removal of the post-reaction sorbent dust from the combustion gas. If the latter caused the increase in combustion gas flow resistance over the permissible level it would be necessary to install the blast fan in the system.

Another problem is a large volume of sorbent required in the desulfurisation process. The vessel would have to carry approx. 17 kg of CaO per each ton of fuel containing approx. 1% of sulfur. For example, in case of 2300 tons of fuel stock it would be necessary to carry approx. 40 tons of sorbent. In such circumstances the management of desulfurisation reaction products would cause a serious problem, e.g. Maj [6].

3 Concept design of fluidised bed waste heat boiler

Considering the operation conditions, sizes and equipment installation conditions in the vessel machine shaft as well as so far experiences learnt from on-land installations of various type fluidised bed waste heat boilers and their relatively low heating capacity, the best design solution seems the system of the fluidised bed waste heat boiler with a stationary bed. The system of the waste heat boiler with a circulating bed is practically useless due to remarkably large size of the sorbent grain separation and regain system. Moreover, that type boilers have to provide significantly higher fluidising agent flow speed values (in that case the speed of outlet combustion gas) that, in turn, would result in flow resistance increase and intensification of erosion of boiler elements having direct contact with the bed. In practice, it would require to have an auxiliary fan installed to support the combustion gas flow. On the other hand, that type boilers should not be sensitive to vessel tilts but that thesis has not been confirmed due to the lack of experiences with marine systems so far.

The requirement, imposed on a fluidised stationary bed waste heat boiler, to provide the appropriate and relatively low combustion gas flow speed while its way through the boiler, would result in too large size of an individual bed. In case of a waste heat boiler it would be compulsory to partition the fluidising bed to several segments (modules). The bed partitioning to independent segments arises not only from the bed size but also the requirement of maintaining the relevant fluidisation conditions when the main engine is not operating in full. It should be pointed out that the number of modules can be increased and that fact makes the system construction more complicated but in the same time, provides more design variants to adapt the system to conditions partial loads of the engine. Partial load of the engine results in reduction of combustion gas flux volume that would cause the fluidisation process to cease. The problem can be solved by the reduction of the cross section surface where the combustion gas flows through, i.e. by cutting off the gas inflow to individual modules. Such a solution would enable to maintain fluidisation speed at the required level and in the same time, support the sufficiently effective boiler operation. The solution, however, is burdened with a certain disadvantage. In case one or more modules are disabled (depending on the engine load) the total surface involved in heat exchange process is significantly reduced. The latter results in boiler efficiency reduction (however, in certain circumstances it can provide a good method of boiler efficiency adjustment).

Another solution is to abandon combustion gas cut off method and to produce the steam exclusively at engine load over 60-70%. At partial load the combustion gas flux should be directed through the by-pass pipeline.

The solution proposed provides partitioning of a stationary bed to three autonomous modules. Each module comprises its individual water pre-heater sub-system, evaporation sub-system and possibly steam super-heater sub-system as well as an independent pipeline for the combustion gas intake.

The super-heater sub-system could be installed in case of significantly high man engine power. The water flow is enforced with a circulation pump. There is no individual steam-water drum in the boiler so the boiler can work only jointly with an auxiliary fired boiler or an autonomous steam separator.

It would be necessary to install anemometers in the boiler to measure the speed of combustion gas flowing through the bed. The anemometers would be coupled with automation systems cutting off the combustion gas inlet to individual modules if the combustion gas speed, during its passage through the bed, drops down to the value slightly higher than critical fluidisation speed.

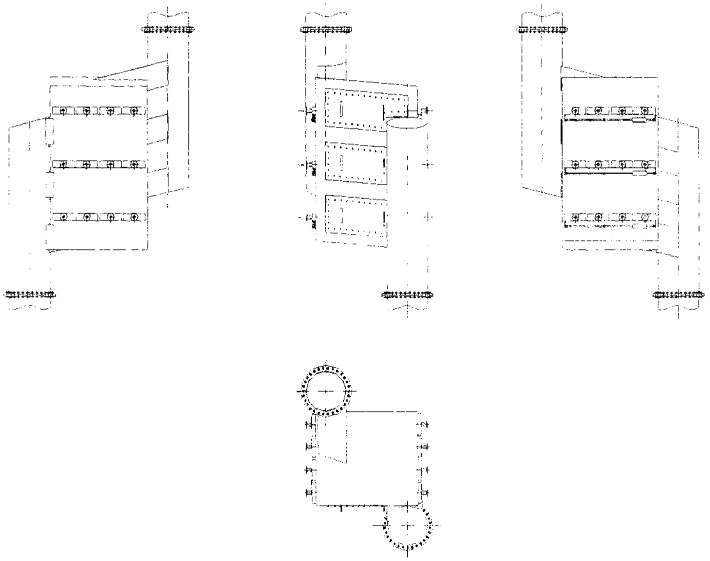

Figure 1: General view of fluidised bed waste heat boiler

Each module is partitioned to four sections. Each section consists of rectangular panels, each of which has an individual grate to separate the combustion gas. The solution of panel partitioning allows to satisfy the requirement of sufficiently stiff system construction resistant to vibrations where its elements are easy replaceable in case of any damage. The main reason of module partitioning is, however, the reduction of free surface of the fluidised bed (the fluidised bed behaves like a liquid) to delimitate the unfavourable "overflow" of the bed during vessel tilting and possibility of heating surface to lay uncovered.

Although the uncovered heating surface can hardly be damaged such an exposition would essentially affect the heat penetration coefficient and subsequently, the boiler efficiency. The smaller panel dimensions the higher resistance of the bed to sea wave related vessel motions. The risk the "dead calm zone" occurs during the vessel tilting, i.e. lack of fluidisation due to the small bed height, is insignificant. The bed height is determined with maximum permissible drop in pressure that depends, as mentioned beforehand, on the density of bed material and the size and shape of sorbent grains. The speed of combustion gas flow should, to provide the best conditions for heat exchange, be at least as twice as critical fluidisation speed value (the critical fluidisation speed denotes the speed value at that moment when the air pressure starts to balance the solid height static pressure).

The structure requires to have the separating overflow-free grate installed which in practice disables discharging of the bed material to the space under the grate. The bed material of the fluidised bed waste heat boiler should be, first of all, highly resistant to erosion and chemically neutral against the combustion gas.

3.1 Selected presumptions and calculation parameters

The considerations on boiler concept design and the selected calculations were limited to gas side aspects since the main problems occur there. The boiler steam-water cycle does not differ much from the same of a conventional water-pipe waste heat boiler with enforced circulation.

For the purpose of calculations it was presumed that the boiler is supplied with combustion gas flux from the engine outlet, of temperature 230^{O}C and volume 28,2 kg/s.

In the result the boiler structure parameters are the following:

number of modules:	3 (each equipped with an independent combustion gas inlet activated depending on combustion gas flow speed and 1 layer of smooth pipes)
number of sections in a module:	4 (ensuring the grate stiffness and preventing the bed from overflowing)
type of separating grate:	overflow-free ash capture system
free section of grate:	10%
grate hole diameters:	0,002 m
bed material:	quartz sand
unmovable bed height:	0,1 m
critical fluidisation speed:	0,707 m/s
combustion gas flow speed:	2,0 m/s
combustion gas pressure drop in unmovable bed:	1031 Pa
combustion gas pressure drop in movable bed:	1471 Pa
grate pressure drop:	595 Pa
separation space height: (the space above the bed ensuring the solid suspended particles separation and return to the bed)	0,42 m
horizontal scale:	0,042 m
external pipe diameter:	0,0213 m
coefficient of heat transfer from the bed to the pipes:	230 W/m^{2}K
sulfur sorbent:	CaO
sorbent consumption:	17 kg/ 1000 kg fuel

4 Comparison between the fluidised bed waste heat boiler and conventional waste heat boiler

On having compared the two types of boilers the fluidised bed waste heat boiler shows several advantages, in particular:

- The steam volume generated can be larger than in conventional boilers of the same heat exchange surface due to higher coefficients of heat transfer from the bed to the heating surface and uniform distribution of temperature within the entire bed domain. (in the example presented the said coefficient value is 230 W/m^2K; in conventional boilers the coefficient value is approx. 150 W/m^2K, e.g. Zeńczak [7]).
- The mechanical method of grate cleaning provides higher effectiveness of residue removal process and eliminates the need of black blower installation.
- Significantly lower risk of boiler fire (ignition of black or other flammable solid particles that can deposit during boiler operation).
- Neither the black nor other compounds are deposited on the external surfaces of the pipes forming the heating surface. The pipes remain clean due to intensive motion of the bed material particles. It ensures high stability of the heat transfer coefficient during the entire exploitation period.
- The heating section panels provide their fast replacement in case of failure or damage.
- A Fluidised Bed Waste Heat Boiler serves as a very effective silencer as well.

The disadvantages of a fluidised bed waste heat boiler include:

- Higher drop in combustion gas pressure than in conventional boiler design solutions (in the example presented and movable bed it equals to 2066 Pa; in conventional waste heat boilers it equals to approx. 1500 Pa).
- The loss in bed material during boiler operation due to corrosion or particle blowouts where the particle diameters became smaller than their critical size. Therefore, the volume of bed material has to be continuously checked and refilled to maintain the required bed height.
- The larger final size of a fluidised bed waste heat boiler than of a conventional waste heat boiler due to e.g. lower speed of combustion gas flow through the boiler or the need to provide the separating space or the need to install external devices such as motors driving the cleaning brushes or inertial material separators.

- The reduction in heating surface area during boiler operation in conditions where the main engine is only partially loaded (cutting off the combustion gas inflow to one or a few sections), that affects boiler efficiency.

- More complicated structure sensitive to vessel tilts.

- More complex automation systems to control boiler operation (checking and adjusting the combustion gas flow speed within a particular interval by means of cutting off the combustion gas inflow to the beds and water inflow to non-operating sections; checking the pressure drop).

5 Conclusion

The recent investigations have revealed that one of the potential development directions in the field of marine waste heat boilers can be the fluidised bed waste heat boilers. The application of a fluidised bed waste heat boiler, possibly equipped with a combustion gas desulfurisation system, in conjunction with SCR method to reduce nitrogen oxides, can provide a complex solution for removal of toxic compounds from the main engine combustion gas. The process of blowing the sorbent dust into the combustion gas, as in case of conventional waste heat boilers, cannot be taken into account as it would result in heating surface contamination. That problem does not exist in case of the fluidised bed waste heat boilers since the heating surfaces are immersed in the bed and are subject to continuous cleansing by inertial material. To solve the problem of dust separation from the combustion gas the installation of cyclone separators or similar devices is necessary, however it results in the increasing resistance of combustion gas flow. In case of a fluidised bed waste heat boiler the flow resistance values of the boiler itself are similar to maximum permissible values specified by the engine manufacturers. The use of cyclone separator may impose the use of combustion gas flow supporting system, i.e. an additional fan installation.

An essential problem that still needs solving is the management of post-reaction sorbent generated in remarkably big amounts. The simplest solution might be the use of the emptied sorbent bunkers to store the dust and discharge the dust in a port. A disadvantage of such a solution, however, is the occupation of certain part of the vessel cargo carrying space.

A fluidised bed waste heat boiler is a device of higher complexity and less popular than a conventional boiler so the users may be reluctant about using them. The present trends reveal designer's tendency to construct waste heat boilers easy in design and operation making them reliable and user-friendly devices.

It should be emphasized that, regarding all experiences and achievements in design of fluidised bed waste heat boilers gained so far in power engineering, the research and work on that type of boilers should be continued.

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