Design Technology for Supercritical Sliding Pressure Operation Vertical Water Wall Boilers - First report: History of Practical Application and Introduction of Enhanced Rifled Tube -

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A supercritical sliding pressure operation once-through boiler with vertical water wall tubes uses high-cooling-capability rifled tubes for its furnace walls. This type of boiler consists of vertically arranged tubes, instead of a complex spirally wound structure, so that it can improve performance, reliability and economic efficiency.

Mitsubishi Heavy Industries, Ltd. (MHI) started to employ this type of boiler for commercial operation at Unit 1 (700 MW) of the Matsuura Power Plant of Kyushu Electric Power Co., Inc. as the world's first application in 1989, as well as in Units 1 and 2 (700 MW each) in the Kawagoe Thermal Power Plant of Chubu Electric Power Co., Inc. in 1989 and 1990. Since then, MHI has provided approximately 50 units of this type – 10 domestically and 40 overseas – including licensing of the technology. The superiority of this type of boiler has been universally acknowledged, and in recent years, several boiler manufacturers have started to introduce this type.

It has been verified that applying high-cooling-capability rifled tubes to the boiler furnace wall enhances the self-correcting action relaxing the steam temperature imbalance across the furnace water wall outlet section, which is caused by inevitable variations of heat absorption in each part of the water walls. This preferable action encourages not only load follow-up performance, but also durability against the upgraded steam condition, the former of which is required by expanding the introduction of renewable energy and the latter required for the reduction of greenhouse gas emissions.

This report explains the design optimization of the furnace water wall system reflecting operational data, advanced technological methods, and the operating guidelines established based on continuous research and development work on heat transfer and hydrodynamic characteristics for furnace water walls with rifled tubes. Also, this report partially introduces the higher-performance vertical water wall tube boiler using new rifled tubes, which will be detailed in the upcoming document (second report).

1. Introduction

MHI has provided many supercritical sliding pressure operation vertical water wall tube once-through boilers to the market since the late 1980s, and therefore, understands deeply furnace heat flux distribution and heat transfer, as well as the flow characteristics of water wall tubes under various operating conditions. For rifled tubes, MHI has succeeded in overcoming significant

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research and development challenges about heat transfer and flow characteristics by utilizing the latest technology in the field of CFD (Computational Fluid Dynamics) analysis and the supercritical pressure heat transfer and hydrodynamic test facility at the MHI Nagasaki Research & Development Center (MHI-NRDC).

These advanced design and heat transfer technologies allow the improved design of vertical tube boilers that have higher performance, operability and reliability.

2. History of development and some of the epochs in the practical application of Mitsubishi vertical tube boilers

As shown in **Figure 1**, MHI's first supercritical sliding pressure operation once-through boiler was a spirally-wound-type boiler with smooth tubes. However, this boiler had a significant pressure drop at the water wall tubes because its fluid mass velocity was high and the tubes were long. Therefore, there was the problem of flow stability, which is described in the chapters below, together with the disadvantages of not only the increased boiler feed water pump power consumption due to its significant pressure drop but also the complicated structure of the furnace wall.

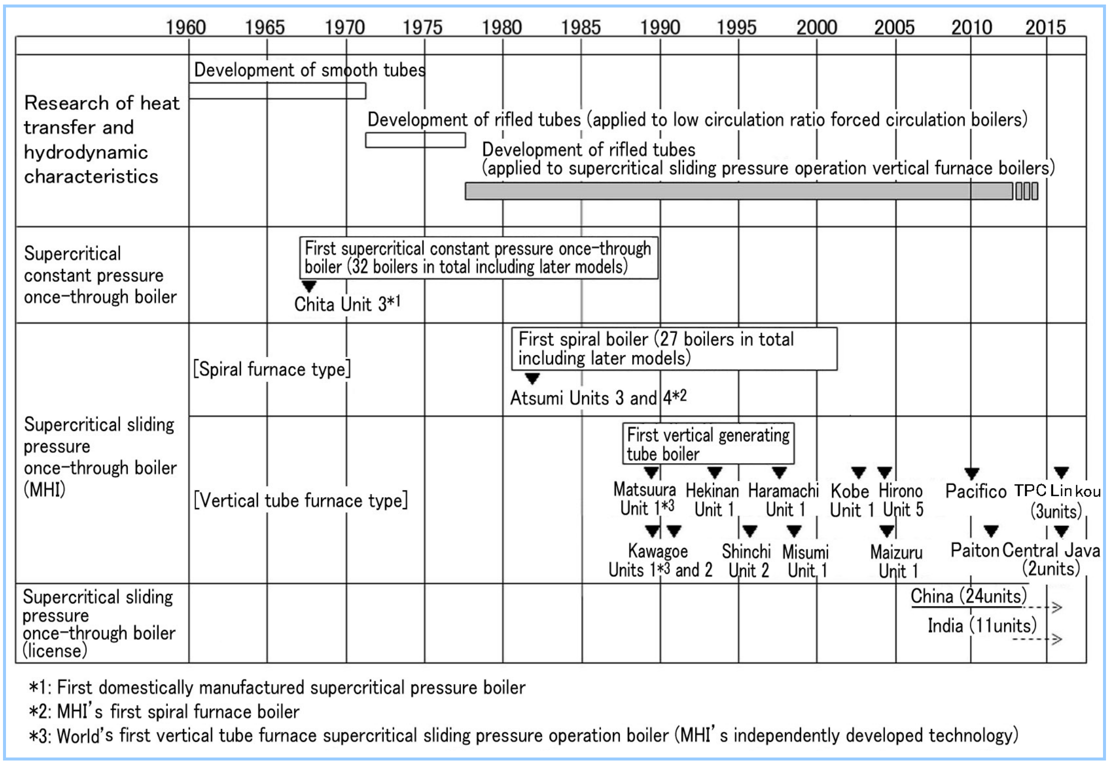


Figure 1 History of MHI's research on heat transfer and hydrodynamic characteristics of boiler evaporator tubes and development of a boiler circulation system

In order to deal with such an undesirable situation, MHI focused on the superior heat transfer and hydrodynamic characteristics of the rifled tubes that had been already put to practical use in subcritical pressure boilers. MHI independently began research and development work on rifled tubes for supercritical sliding pressure operation boilers, and employed the vertical water wall tube type for supercritical sliding pressure once-through boilers.[1]

The first deliveries were Unit 1 (700 MW)[2] of the Matsuura Thermal Power Plant of Kyushu Electric Power Co., Inc., which started commercial operation in 1989, and Units 1 and 2 (700 MW each)[3] at the Kawagoe Thermal Power Plant of Chubu Electric Power Co., Inc., which started operation in 1989 and 1990. These boilers realized simple structure, high performance and high reliability.

Since then, MHI has been moving forward with tireless innovations based on significant operational experience to improve furnace water wall design technologies.[4] As a result, one overseas plant that has recently started operation can maintain a stable temperature profile at the furnace outlet section, even when the furnace outlet enthalpy rises to a large extent, and also has been operated with a good load follow-up rate as high as 5%/min and above[5] (**Figure 2**).

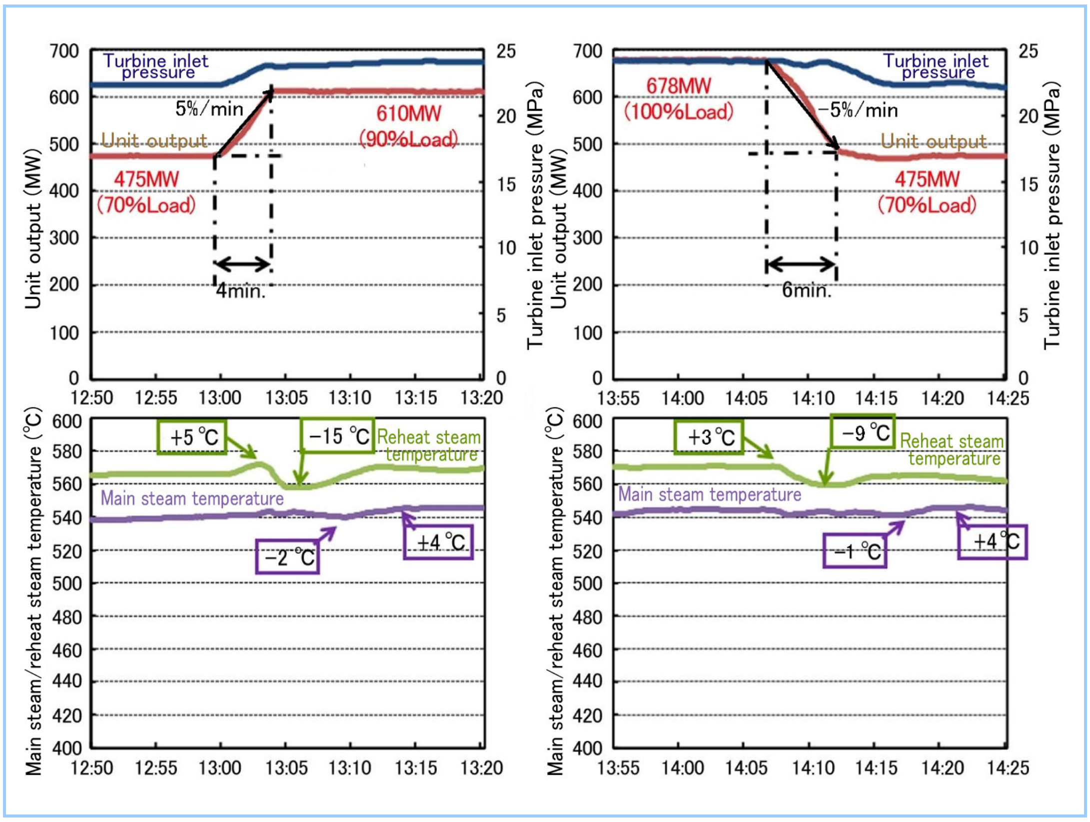


Figure 2 Load follow-up performance at overseas plant (as high as 5%/min)

3. Advantages of Mitsubishi vertical tube boilers

Figure 3 and **Table 1**[6] show the advantages of vertical water wall tube boilers over spirally wound water wall tube boilers.

3.1 Pressure drop characteristics

Vertical tube boilers have smaller pressure drop, and boiler feed water pump power consumption can be reduced in comparison with spirally wound boilers because of the lower mass velocity and shorter tube length of the water wall.

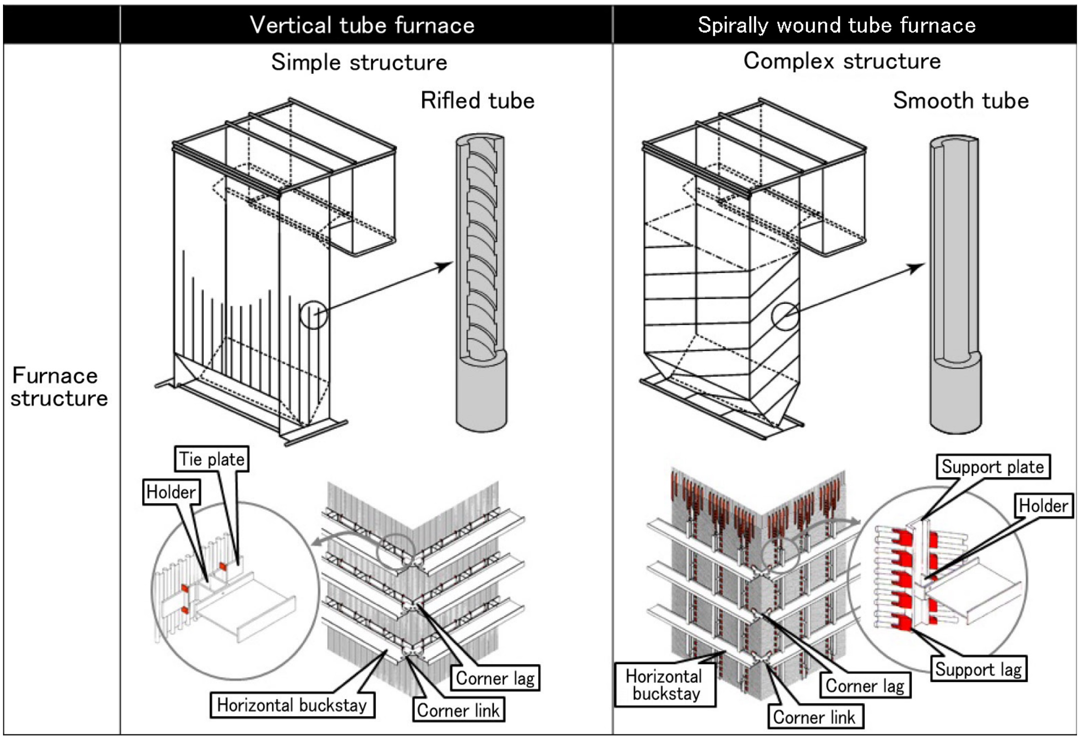


Figure 3 Comparison between vertical tube furnace structure and spirally wound tube furnace structure

Table 1 Superiority of vertical tube boiler

	(A) MHI low mass velocity vertical design	(B) Spirally wound design
Mass velocity @ BMCR	1,000-1,900kg/m^{2}s	3,000kg/m^{2}s
Furnace tube adopted	Rifled tube	Smooth tube
Heat transfer rate of fluid	High	Base
Flow characteristics	Good	Base
Furnace outlet fluid temperature profile (1) High load (2) Low load	(1) Even due to appropriate flow distribution (2) Even due to low mass velocity	Base
Supply record	50 or more boilers since 1989	Many

3.2 Installation aspects

Vertical tube boilers have a simpler structure in comparison with spirally wound boilers, and therefore, the variation of the mechanism for furnace supports, such as stiffeners, attachments and so on can be significantly reduced, resulting in superiority in terms of installation, reliability and maintenance.

3.3 Ash adherence aspects

Because the furnace wall tubes of vertical boilers are placed vertically, ash can fall off easily and this results in a smaller amount of ash adhering to the furnace wall surface. This becomes a significant advantage, especially when high-slag coal such as sub-bituminous coal is used.

3.4 Flow characteristics

For spiral boilers, when the heat absorption of certain water wall tubes increases due to the falling of slag or other factors, the metal temperature of the tubes tends to rise excessively. The reason for this is because the fluid flow is reduced due to the significant increase of friction loss caused by the sharp increase of fluid volumetric velocity resulting from the sharp increase in specific volume. This temperature increase in the furnace wall tube metal may cause deformation of the furnace wall in a short time or shorten the lifecycle by repeated increases in temperature over long periods.

For vertical tube boilers, in contrast, the fluid flow reduction in tubes with such transitional increases of heat absorption as above is lower, and the increase in tube metal temperature is very limited.

The mechanism of this smaller fluid flow reduction in vertical tubes is described below. Even though fluid velocity increases, the increase in friction loss is limited. As for the total pressure drop, the sum of friction loss and static head from the bottom to the top of the furnace water wall does not increase significantly, which results in a smaller reduction of fluid flow.

By investigating deeply this mechanism, if the lower mass velocity in the rifled tube could be attained, the further limited increase in friction loss should be attained to the extent that the total pressure drop could be reduced by a predominant decrease of the static head resulted from the increase in specific volume. This is the preferred nature, the so-called, “natural circulation flow characteristics,” – a fluid flow increase along with a heat absorption increase.

These ideal flow characteristics required an innovation that overcomes the tradeoff where the even lower mass velocity inevitably induces a higher metal temperature. The enhanced new type refiled tube developed by MHI can solve this dilemma.

3.5 Flow stability

Although typical vertical tube boilers have good flow characteristics as described above, it must be considered that the extremely low mass velocity would worsen the flow stability because there would be a concern that the fluid flow rate might be reduced too much when heat absorption changes.

Based on design technology and many examples of actual applications of vertical tube boilers, MHI optimizes furnace water wall tube hydrodynamic characteristics depending on the selected mass velocity in order to avoid worsening the flow stability and ensuring good flow characteristics.[7]

In addition, unstable flow (density-wave oscillation) may occur due to the void rate, pressure drop and/or flow rate transfer lag in the flow path system. It is generally known that density-wave oscillation has a greater tendency to occur when the inlet flow rate is lower and also when the inlet pressure is lower. A vertical tube boiler with low mass velocity may have issues with the occurrence of density-wave oscillation during low load operation at a low fluid pressure. This is one of the considerations in designing vertical tube boilers.[8]

3.6 Load follow-up capability

When the load change rate is small, the amount of fuel and water fed into the furnace is adjusted so that both inputs are balanced. When the load change rate is large, on the other hand, the temperature of the superheater (SH) and reheater (RH) may deviate from the rated temperature because in addition to the heat absorption of the furnace, SH and RH are also affected by heat input fluctuations. In other words, the steam temperature deviation of SH and RH may constitute a certain limit to the rate of load change, and therefore, a fuel and water feeding method that does not enlarge the steam temperature deviation of SH and RH is key to improve the rate of load change (**Figure 4**).

When the rate of load change is large, the amount of fuel and water fed into the furnace transiently needs to be changed significantly, individually and quickly in comparison with a steady condition. Therefore, the employment of a furnace water wall system with good flow characteristics and flow stability contributes essentially to the improvement of the rate of load change.

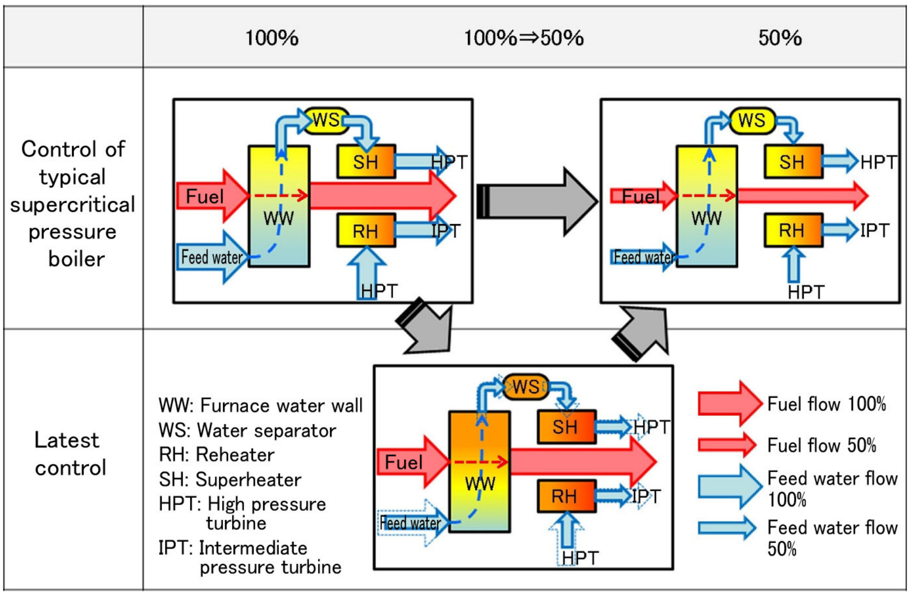


Figure 4 Load follow-up performance of the latest vertical tube boiler high rate of load change

4. Matured technologies necessary for optimum design of vertical tube boilers

Key factors in the design process of a furnace water wall with rifled tubes in supercritical sliding pressure operation boilers are:

- To prevent heat transfer deterioration, such as DNB (Departure from Nucleate Boiling) in the subcritical pressure region and in the supercritical pressure region
- To minimize the fluid temperature imbalance at the furnace outlet section

The accumulated experience of MHI's design technology for the above is presented below.

4.1 Vast data accumulated through continuous development work on rifled tubes

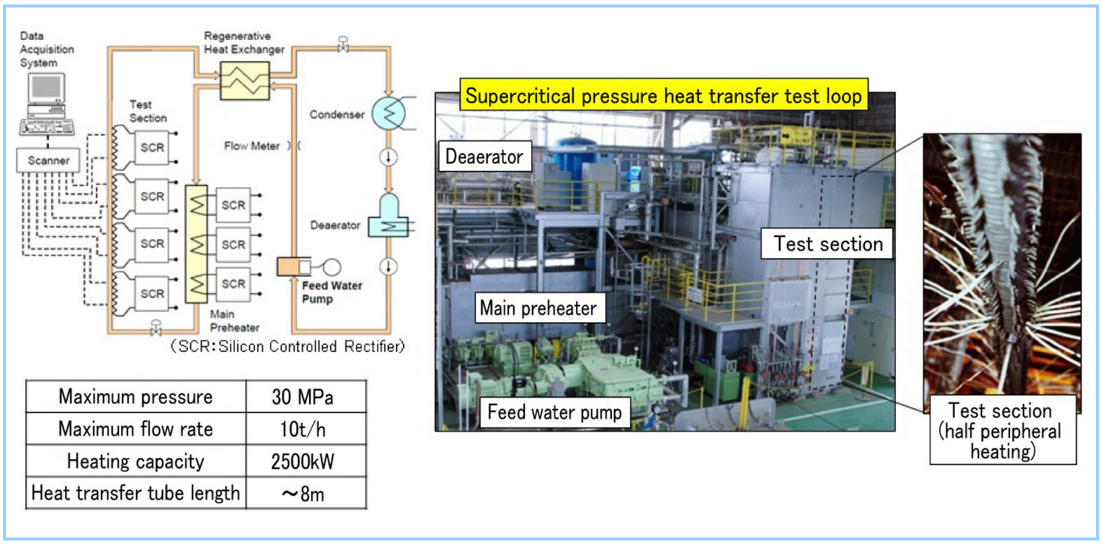
There have been studies for a long time on internally grooved tubes as typified by rifled tubes.[9] Many researchers have reported the heat transfer deterioration phenomena in which the tube wall temperature sharply rises incurred by the increase of heat flux or the decrease of mass velocity.[10-13]

MHI started heat transfer and hydrodynamic tests in large diameter rifled tubes for natural circulation boilers and smooth tubes in the 1960s when high temperature and high pressure heat transfer test facilities were established at MHI-NRDC. In 1979, the supercritical pressure heat transfer test loop (**Figure 5**) was established. Some of the test results were collected into the first paper, which was presented at the 7th International Heat Transfer Conference in 1982.[14] This was the world's first paper that described in detail the relationship between the heat transfer coefficient and the pressure near critical pressure, both for rifled tubes and smooth tubes. Since then, MHI has been acquiring data systematically and continuously, and a huge amount of data about the heat transfer and hydrodynamics of rifled tubes have been accumulated.[15]

Some experimental research reports have been made by other companies or laboratories as follows. Ackerman[16] reported the inhibitory effect of rifled tubes on heat transfer deterioration in the supercritical pressure range. Nishikawa et al.[17] found that supercritical pressure heat transfer deterioration occurred even with rifled tubes and the possibility of heat transfer deterioration might depend on the ribbed shape (internally grooved shape). In recent years, J. Wang[18] and J. Pan et al.[19] also reported on the supercritical pressure heat transfer characteristics of rifled tubes.

In the 1990s, some reports[20-23] about CFD analysis on supercritical pressure fluid were presented, but they covered comparatively simple shapes such as smooth tubes. MHI has independently established an analysis method for supercritical pressure heat transfer fluid with rifled tubes and is proceeding with effective research and development using CFD analysis.

The new rifled tubes described in this report, which comprise the heart of the technologies used in the latest vertical tube boiler, have been developed based on vast amounts of test data accumulated over the years by combining the most advanced CFD analysis methods and the evaluation based on experiments using the supercritical pressure heat transfer test loop at MHI-NRDC.



Maximum pressure	30 MPa
Maximum flow rate	10t/h
Heating capacity	2500kW
Heat transfer tube length	~8m

Figure 5 Supercritical pressure heat transfer test loop at MHI-NRDC

4.2 Detailed heat transfer characteristics of actual boilers

In a supercritical sliding pressure operation once-through boiler, the pressure varies from the subcritical pressure region to the supercritical pressure region, and there occurs, in the furnace water wall tubes, various modes of heat transfer phenomena including forced convection heat transfer (nucleate boiling heat transfer and film boiling heat transfer) of single liquid phase (water), single vapor phase (steam), and vapor-liquid two-phase (steam and water) flow, as well as supercritical pressure heat transfer. Therefore, it is essential to have a mature analytical method for each mode of heat transfer phenomenon for optimized furnace water wall system design.

MHI has comprehensive analytical technologies for all aspects based on MHI's test data and experience with actual boilers. **Figure 6** shows the evaluation of heat transfer phenomena of rifled tubes at various pressures.

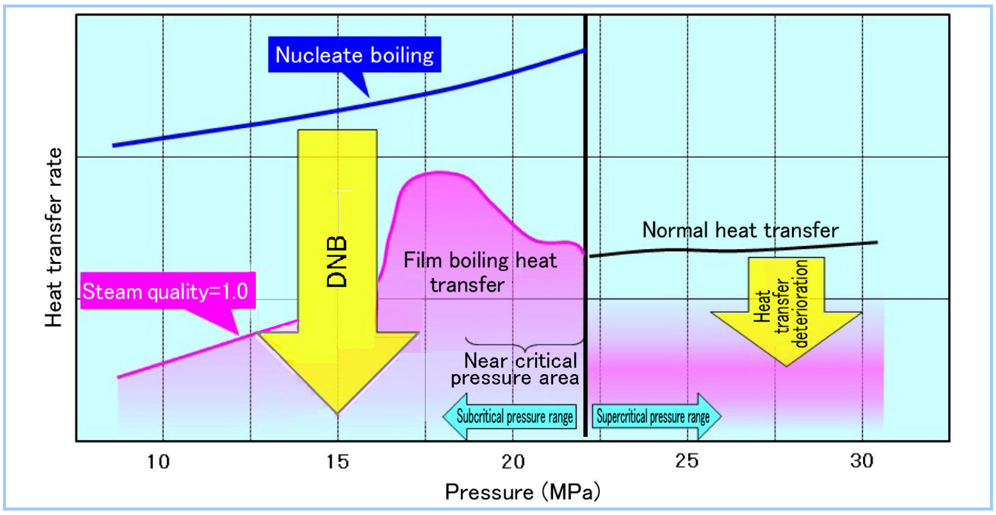


Figure 6 Evaluation of heat transfer phenomena of rifled tubes at various pressures

4.3 Accumulation of heat flux data based on experience with actual boilers

When operated at partial load at supercritical pressure, the specific heat of the steam at the outlet of the furnace water wall is comparatively small and a steam temperature imbalance at the same elevation of furnace wall caused by the deviation of heat absorption tends to occur, and therefore, it is important for the mechanical design of the furnace walls to take into account this temperature imbalance.

MHI employs a circular firing system for its boilers to attain efficient combustion. As a result, the furnace heat flux distribution is milder than that of opposed or front firing boilers, but still occurs to a certain extent. MHI has designed a flow-balanced furnace water wall system based on various data with actual boiler and analysis technologies to minimize the outlet enthalpy difference (temperature difference) between the furnace wall tubes caused by the difference in heat flux distribution depending on the coal type used or the boiler load. For coal-fired boilers, it is necessary to take into consideration the intermittent fluctuation of the heat absorption of the furnace wall tubes caused by the falling of slag adhered to the furnace wall, and also robust design that accommodates various patterns of heat absorption is important.

MHI can consider any heat absorption pattern using the accumulated operating data of many vertical tube boilers and has succeeded in attaining stable temperature characteristics at the furnace wall outlet under all operating conditions by flow adjustment in the furnace wall tubes and optimization of the entire water wall system, which also includes the furnace exit connecting tube, etc.

5. Optimized selection of mass velocity for vertical tube boilers

5.1 Furnace sectional heat flux and mass velocity selection

The key factors in designing vertical tube boilers described in section 4.2, namely heat transfer deterioration and temperature difference at the furnace outlet, are closely related to the mass velocity of the fluid in furnace water wall tubes. In the design process, the mass velocity is not selected randomly but typically determined considering the following conditions:

(1) Flow rate through furnace water wall tubes

In general, the flow rate is subject to the unit power output depending on the steam condition and spray amount of a desuperheater.

(2) Number of furnace wall tubes

MHI employs membrane walls, consisting of tubes and fins. The pitch of the furnace wall tubes is selected, taking into account how much the fins are cooled. The number of furnace wall tubes generally depends on the pitch and the peripheral length of the furnace, the latter of which is linked to its cross-sectional area.

The selection of the furnace size (cross-sectional area, volume, etc.) is made by taking into account not only the unit power output, but also the slagging characteristics of the furnace, for which MHI can make a suitable selection based on its vast experience with various types of fuel.

(3) Fluid flow sectional area of furnace water wall tube

The fluid flow sectional area depends on the tube specifications such as outer diameter, wall thickness, etc.

The required minimum wall thickness of the furnace water wall tubes is determined individually in terms of tube material and mechanical strength against pressure and temperature, which limits the range of mass velocity to a certain extent.

5.2 Relationship between furnace water wall tube heat transfer characteristics and mass velocity

The conditions at which the DNB phenomenon occurs in the subcritical pressure range represented with mass velocity and steam quality are shown in **Figure 7**.[24] DNB occurs in the area where the quality is higher than each solid line. As shown in this figure, the upper limit of the steam quality where a rifled tube can suppress DNB is higher than that of a smooth tube. Generally, in once-through boilers using smooth tubes, it is unavoidable to have DNB and resultant film boiling at the furnace water wall tubes, and it is also well known that the lower the steam quality, the lower the heat transfer rate becomes in film boiling, then it is important to keep the mass velocity high so that cooling capability can be kept as high as possible to properly suppress the temperature rise. When a rifled tube is used, on the other hand, DNB can be prevented at higher steam quality, even when the mass velocity is low.

In the similar manner as Figure 7, the heat transfer deterioration conditions in the supercritical pressure range represented with mass velocity and heat flux are shown in **Figure 8**[24], in which heat transfer deterioration occurs in the area where the heat flux is higher and the mass velocity is lower. If heat transfer deterioration occurs, the tube wall temperature can rise sharply, and the safety of the furnace water wall may not be maintained.

Heat transfer deterioration causes wall tubes not only short-term creep rapture, but also fatigue damage with abrupt temperature changes generated by heat flux fluctuations. In the latter case, corrosive thinning such as groove corrosion (or so-called alligator cracking) may occur after many amount of temperature change. Therefore, heat transfer deterioration is one phenomenon that needs to be avoided.

As described in section 4.1, the occurrence conditions of heat transfer deterioration may differ depending on the shape of the rib. For improvement in the reliability of vertical tube boilers, it is important to develop rifled tubes that are unlikely to exhibit heat transfer deterioration, even at low mass velocity and high heat flux.

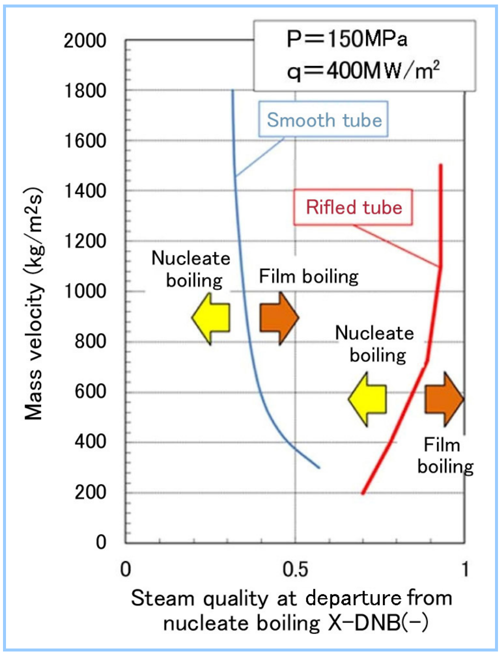


Figure 7 DNB characteristics of rifled tubes and smooth tubes at subcritical pressure

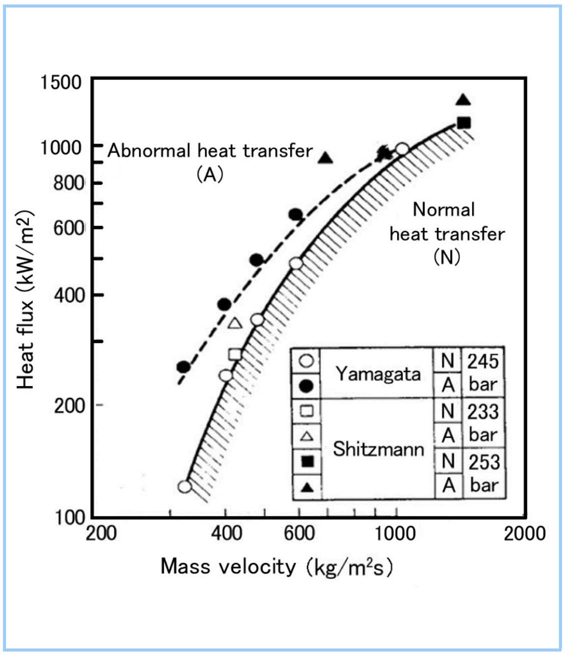


Figure 8 Conditions where heat transfer deterioration occurs at supercritical pressure (smooth tube)

5.3 Development of new rifled tubes

Rifled tubes that suppress not only DNB at subcritical pressure but also heat transfer deterioration at supercritical pressure are preferable as described in section 5.2. It is generally acknowledged that an effective method for DNB suppression at a subcritical pressure range is to make the rib higher and the lead angle larger against fluid flow. In addition, it is suggested that the rib shape also has a significant influence on heat transfer deterioration at supercritical pressure as described in section 4.1. MHI has developed rifled tubes that can avoid both DNB at subcritical pressure and heat transfer deterioration at supercritical pressure, and is applying them to actual boilers. In this development, MHI revealed the relationship between the internal groove shape and the heat transfer characteristics of rifled tubes by analyzing in detail test data acquired and accumulated with various shapes of rifled tubes, and used the latest CFD analysis techniques (**Figure 9**) to evaluate the heat transfer deterioration mechanism. At the supercritical pressure heat transfer test loop in MHI-NRDC, MHI has also verified that the new rifled tubes developed in this way have good performance throughout actual pressure and temperature (**Figure 10**).

Although it has been imagined that an effective method for DNB suppression is to make the rib higher and the lead angle larger against fluid flow, several researchers[18][19] have reported that rifled tubes designed in such a way tend to exhibit heat transfer deterioration at supercritical pressure. Therefore, MHI used both CFD analysis and the supercritical pressure heat transfer test loop at MHI-NRDC to carefully verify the selection of the rifled tube specifications that can suppress both DNB at subcritical pressure and heat transfer deterioration at supercritical pressure. Over the entire development process, from the planning of the concept to actual boiler application, the combination of CFD analysis and verification at the test loop has worked effectively for development.

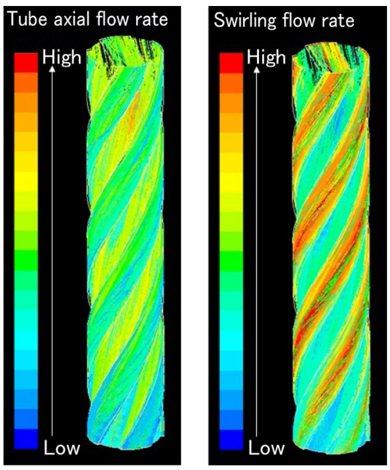


Figure 9 Analysis of rifled tube based on CFD analysis

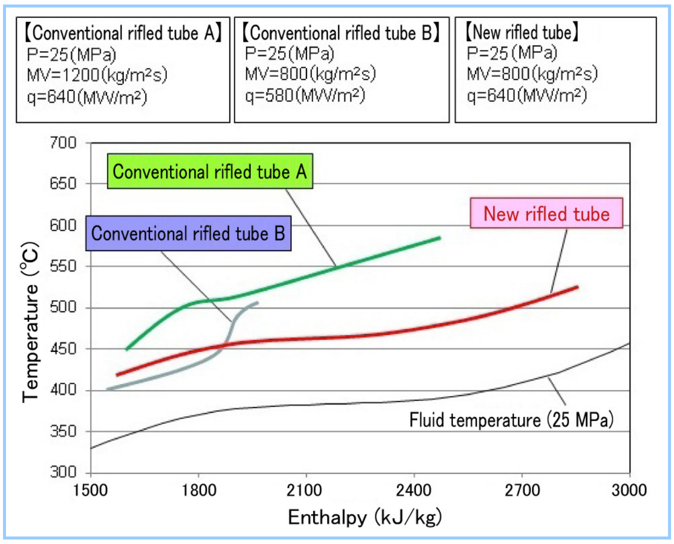


Figure 10 Heat transfer characteristics of new rifled tube

5.4 Boiler design for application of new rifled tube

The bottleneck caused by heat transfer deterioration as described above has now been cleared, and the sufficiently low-mass velocity design becomes possible. The latest vertical tube boiler with the improved rifled tube attains good flow characteristics and fluid stability in the furnace water wall. In addition, by employing advanced furnace design technologies, it has the prospect of meeting further higher steam parameters. A detailed verification will be presented in the next report.

6. Conclusion

This report describes the design technologies used for the latest supercritical sliding pressure operation vertical tube boiler, which significantly improves the heat transfer and hydrodynamic characteristics of the furnace water wall. This type of boiler has been realized and will succeedingly provide higher operability and reliability, using advanced design technologies based on continuous development work on rifled tubes and vast experience with actual boilers.

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