

# Benson low mass flux vertically-tubed evaporators in the power market



A status update

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# BENSON low mass flux vertically-tubed evaporators in the power market

A status update

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Over the period from the early to mid 1990s, critical basic patents were applied for and granted in the context of the BENSON licence, protecting the design of vertically-tubed evaporators with low mass flux and the use of optimised rifled tubes for BENSON boilers.

Key elements of the new evaporator concept were the so-called positive flow characteristic and the use of optimised inside rifled tubes for fired boilers with high heat flux in the furnace or the use of smooth tubes or standard rifled tubes in circulating fluidised bed systems with low heat flux. For heat recovery steam generators with a horizontal gas path, a concept was developed and patented for a once-through evaporator with vertical heat exchange tubes and a positive flow characteristic.

Vertical tubing based on the BENSON low mass flux design has since been introduced to the market by the BENSON licensees, and there are many highly successful references worldwide for both heat recovery steam generators as well as boilers with separate firing.

## Fundamental principles

A range of aspects must be tested and investigated in the thermohydraulic design of an evaporator heat exchange surface for a modern once-through boiler:

- An evaporator heat exchange surface is constructed from a large number of heat

exchange tubes configured in parallel. The feedwater that is typically preheated in an economiser is supplied to the heat exchange surface and is distributed to the individual tubes.

- Flow through these parallel tubes is not uniform due to differences in tube geometry, for example resulting from tolerances in wall thickness, from offset tubes at burners or due to the geometry of the furnace and from differences in heat input. The fluid temperatures at the outlet from the individual heat exchange tubes are therefore non-uniform. These differences in temperature and mass flux are known as imbalances. Imbalances must be reduced to the extent that neither impermissible stresses between adjacent tubes nor violations of the maximum permissible material temperatures result.
- The distribution of the feedwater to the individual evaporator tubes is ultimately determined by the pressure drop across the distributor, the headers and the heat exchange tubes. Calculation of the pressure drop and the flow distribution in the evaporator heat exchange surfaces taking into account heat input is therefore of critical importance.
- Tube cooling and material temperatures and stresses are calculated and flow stability checked, taking into account the determined imbalances.

These characteristics have been



Figure 2. Cutaway showing the inside of a rifled evaporator tube

exhaustively examined and appropriate design features successfully implemented under the BENSON licence.

Extensive measurements of pressure drop and heat transfer have been performed on smooth tubes in the BENSON laboratory in Erlangen since the mid 1970s, as well as on rifled tubes, since development of the BENSON low mass flux design. Roughly 282 000 data sets for smooth tubes and about 285 000 data sets for rifled tubes are currently available. The results obtained have been incorporated into calculation programs available to Siemens and the BENSON licensees.

Figure 1 provides an overview of heat transfer and pressure drop investigations performed on the BENSON test facility since 1975.

The evaporator heat exchange surfaces exhibit a so-called positive flow characteristic as a result of the low mass flux in the BENSON low mass flux design and the associated low frictional pressure drop. The mass flow rate in tubes with higher heat input is greater than that in tubes with lower heat input. The positive flow characteristic therefore helps to limit the effects on the imbalances from differences in heat input due to factors such as firing characteristics.

Further design measures for reducing imbalances can be investigated and implemented based on exact knowledge of the flow distribution in the evaporator heat exchange surfaces.

As the heat transfer rates and material temperatures can be exactly calculated, the appropriate tube type and the required design mass flux can be selected for each evaporator heat exchange surface.

In the BENSON low mass flux design, the vertical evaporator tubes in the lower furnace are designed for an average full load mass flux of roughly 1000 kg/(sm<sup>2</sup>) in the case of pulverised coal firing. This uses rifled tubes, the geometry of which was modified by the BENSON designers in collaboration with several manufacturers. These tubes are known as optimised rifled tubes.

Figure 2 shows the inside of a rifled evaporator tube.

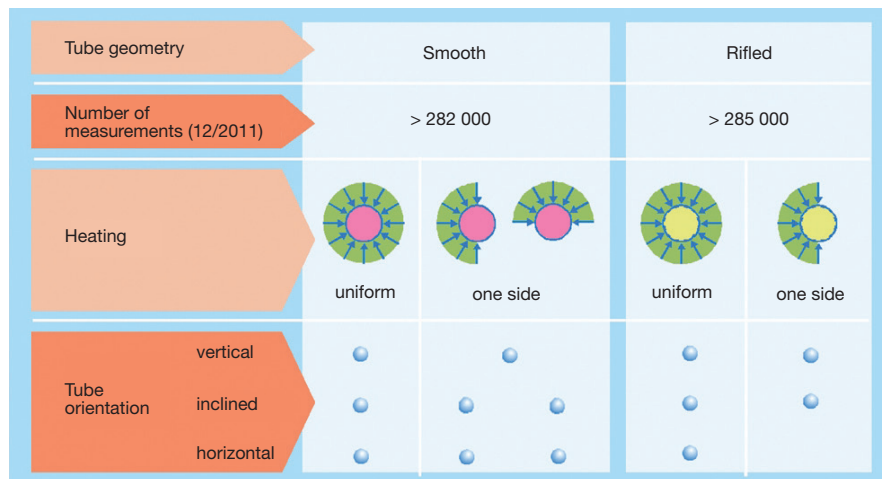


Figure 1. Overview of heat transfer and pressure drop investigations on the BENSON test facility, Erlangen, Germany, since 1975

**Table 1. Boilers for bituminous coal**

Name of plant	No. of units	Size	Manufacturer	Type
Yaomeng 1	1	300 MW	Mitsui Babcock Energy	subcritical
Longview	1	750 MW	Foster Wheeler	supercritical
Yaomeng 2	1	300 MW	Doosan Babcock Energy	subcritical
Rayong	1	700 MW	Doosan Heavy Industries	supercritical
Buk Pyeong	2	660 MW	BHI	supercritical

**Table 2. Supercritical boilers for anthracite coal**

Name of plant	No. of units	Size	Manufacturer
Jinzhushan	1	600 MW	Babcock & Wilcox Beijing
Xing Yi	2	600 MW	Babcock & Wilcox Beijing
Xing Yang	2	600 MW	Babcock & Wilcox Beijing
Gongxian	2	600 MW	Dongfang Boiler
Fuxi	2	600 MW	Dongfang Boiler
Nanning	2	660 MW	Dongfang Boiler
Heshan	1	660 MW	Shanghai Boiler
Zhenxiong	2	600 MW	Harbin Boiler
Weixin	2	600 MW	Dongfang Boiler
Tongzi	2	600 MW	Dongfang Boiler
Zhuzhou B	2	600 MW	Dongfang Boiler
Chayuan	2	660 MW	Dongfang Boiler
Zhijin	2	600 MW	Dongfang Boiler
Vinh Tan 1	2	620 MW	Dongfang Boiler

**Table 3. Supercritical CFB boilers**

Name of plant	No. of units	Size	Manufacturer
Lagisza	1	460 MW	Foster Wheeler Energia
Novocherkasskaya	1	330 MW	Foster Wheeler Energia
Baima	1	600 MW	Dongfang Boiler
Samcheok	4	550 MW	Foster Wheeler Energia
Guojin	2	350 MW	Dongfang Boiler
Hequ	2	350 MW	Dongfang Boiler

A significantly lower full-load mass flux can be selected in boilers employing a circulating fluidised bed due to the moderate heat input. Standard rifled tubes or smooth tubes or a combination of these two tube types can be used in the evaporator in this application.

The use of smooth tubes in the evaporator is also sufficient for heat recovery steam generators.

A further important aspect for a reliably operating design is flow stability within the evaporator. In the static stability analysis a check is carried out as to whether individual tubes or groups of tubes in the evaporator can have more than one operating point with identical boundary conditions. This requires a large number of (relatively straightforward) pressure drop calculations and their corresponding analysis.

The physical phenomena governing the dynamic stability of two-phase flows and the theoretical basis have been investigated, understood and documented in the

context of the BENSON licence. By the mid 1980s, oscillations measured in a power plant had already been correctly calculated quantitatively using non-linear simulation.<sup>1,2</sup>

A test stand with tubes configured in parallel was installed in the BENSON laboratory in Erlangen in 2014 for further investigation of the phenomenon. This setup enabled, for the first time in the world, the reproducible generation and observation of dynamic instabilities in vertically configured heated tubes with a geometry typical for BENSON evaporators, under laboratory conditions. The purpose of the tests was to destabilise an initially stable flow in the tubes by changing a parameter and to generate a mass flow oscillation. This stability threshold was investigated in many measurement periods with variation of the parameters of pressure, mass flux, subcooling at the inlet and superheating at the outlet.

The tests are currently being evaluated to

further validate the programs for dynamic stability simulation available at Siemens.

### Projects and references

Tables 1-4 list references for the BENSON low mass flux design.

The first pulverised-coal-fired plant was Yaomeng 1 in China, which started operation in May 2002. This was a modification project in which large portions of the pressure section were replaced.<sup>3</sup> The first new construction project was the supercritical boiler for the Longview project, which was handed over to the customer in 2011.<sup>4</sup>

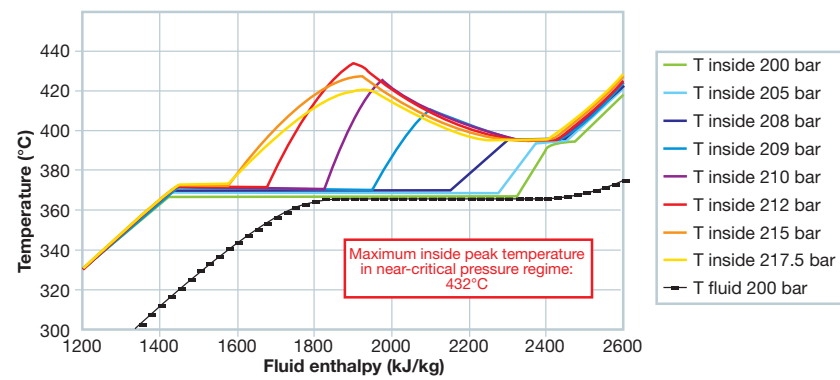
A further important application for the BENSON low mass flux design is boilers for firing anthracite. The complex furnace geometry renders the implementation of vertical tubing almost absolutely essential. The first project was the Jinzhushan plant, commissioned in early 2009.<sup>5</sup>

Vertical tubing with low mass flux has also been deployed in supercritical plants with circulating fluidised beds. The Lagisza

**Table 4. HRSGs**

Name of plant	No. of units	Power output	Gas turbine	Manufacturer
Cottam	1	~ 390 MW	SGT5-4000F	Deutsche Babcock
Herdecke	1	~ 400 MW	SGT5-4000F	Ansaldo Caldaie
Hamm-Uentrop	2	~ 800 MW	SGT5-4000F	Ansaldo Caldaie
Langage	2	~ 885 MW	GT26	Alstom
Lingen	2	~ 850 MW	GT26	Alstom
Irsching 5	2	~ 820 MW	SGT5-4000F	STF
Sloe Centrale	2	~ 870 MW	SGT5-4000F	CMI
Severn Power	2	~ 870 MW	SGT5-4000F	CMI
Gönyü	1	~ 400 MW	SGT5-4000F	STF
Malzenice	1	~ 400 MW	SGT5-4000F	STF
Pego	2	~ 870 MW	SGT5-4000F	NEM
Irsching 4	1	~ 530 MW	SGT5-8000H	Siemens
Joetsu 1- 3	6	~ 1560 MW	GE F7FA+e	Babcock-Hitachi
Joetsu 4	2	~ 520 MW	GE F7FA+e	Babcock-Hitachi
Lodi	1	~ 284 MW	SGT6-5000F	Nooter/Eriksen
Bugok 3	1	~ 400 MW	SGT6-8000H	BHI
Andong	1	~ 400 MW	SGT6-8000H	BHI
Ansan	2	~ 820 MW	SGT6-8000H	BHI
Panda Temple I	2	~ 700 MW	SGT6-5000F	NEM
Sherman	2	~ 700 MW	SGT6-5000F	NEM
Lausward	1	~ 595 MW	SGT5-8000H	Siemens
Posco 7- 9	3	~ 1200 MW	SGT6-8000H	BHI
Deagu	1	~ 400 MW	SGT6-8000H	BHI
Ceniz Samsun	1	~ 590 MW	SGT5-8000H	Doosan Heavy Industries
Panda Temple II	2	~ 700 MW	SGT6-5000F	NEM
TNB Prai	2	~ 1150 MW	SGT5-8000H	Doosan Heavy Industries
San Gabriel	1	~ 400MW	SGT6-8000H	NEM
Bandirma II	1	~ 600 MW	SGT5-8000H	NEM
Dangjin 4	2	~ 820 MW	SGT6-8000H	DKT

**Figure 3. Calculated temperature profile in the pressure range close to the critical pressure**



plant was commissioned and handed over to the customer in early 2009.<sup>6</sup> The boiler in the Baima plant is currently the largest circulating fluidised bed system in the world. It was handed over to the operator in April 2013.

The first combined cycle heat recovery steam generator with a horizontal gas path, vertical heat exchange tubes and a once-through evaporator was in the Cottam plant, commissioned in 1999. A total of 50 BENSON heat recovery steam generators have since been commissioned and handed over to the customers. Additional units have since been ordered and are in the implementation phase.

In summary, it can be stated that a large number of projects incorporating vertical-tube evaporators and low mass flux have been constructed and commissioned by various BENSON licensees. Market introduction of the BENSON low mass flux design can be regarded as successful.

It is very interesting in this regard to note that, after expiration of the basic patents, manufacturers outside the BENSON licence are now speaking of the benefits of the positive flow characteristic, propagating mass fluxes of 1000 kg/(sm<sup>2</sup>) in the evaporator at full load and claiming to have optimised the geometry of the rifled tubes.

Many vertical-tube evaporators with high mass flux and standard rifled tubes have been constructed and commissioned outside the BENSON licence, although the evaporator tubes have a once-through characteristic. In this case, the mass flow rate in tubes with higher heat input is lower than that in tubes with lower heat input. In order to compensate for the disadvantages of this negative characteristic for imbalances, the flow distribution in the evaporator has been deliberately adjusted using flow restrictors at the inlets to the heat exchange tubes or upstream in the feed lines. Imposing a flow distribution with flow restrictors has the critical disadvantage that it can only be optimised for a single operating point. This renders any flexible response to factors such as changes in heat input impossible for this design.

### The BENSON laboratory

A vertical-tube evaporator cannot be designed for reliable operation at low mass flux without exact knowledge of the heat transfer and the occurrence of various boiling crises such as dryout and the departure from nucleate boiling (DNB), taking into account the tube type, installation orientation and operating conditions. Furthermore, exact knowledge of the pressure drop is of critical importance for determining the mass flow distribution and for analysing the positive flow characteristic for the various operating points of the boiler. Extensive investigations in the BENSON laboratory in Erlangen have revealed the complex relationship between the location of the boiling crisis and the overall pressure drop of the boiler tube under various operating conditions.

An important and early result from the many tube tests was determination of the heat transfer behaviour in the pressure range close to the critical pressure. For both smooth and rifled tubes, a shift in the boiling crisis from high steam qualities (typical dryout behaviour) to extremely low steam qualities (typical behaviour in departure

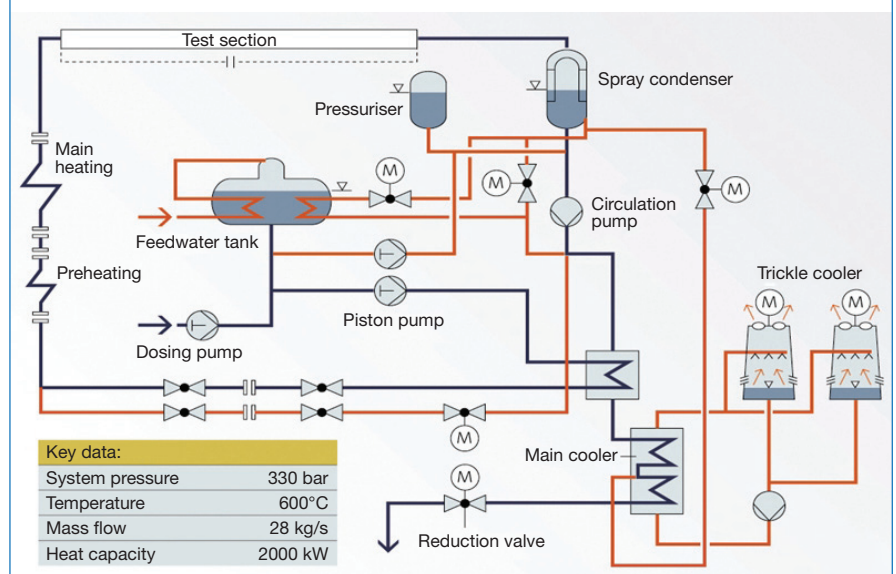
from nucleate boiling) was observed as the critical pressure was approached. The slightest pressure changes in the steady-state tests resulted in large differences in the location of the boiling crisis as well as in the tube wall temperatures established after the boiling crisis. It quickly became clear that a reliable design for a boiler that passes through the critical pressure on load changes requires a very small pressure step size in the heat transfer measurements over the range from 175 to 230 bar.

The range close to the critical pressure above 220 bar is also important, as behaviour similar to the departure from nucleate boiling can occur here. Various fluid properties are established in the supercritical fluid corresponding to the higher temperature in the boundary layer at the inside wall of the tube (comparable to the steam phase) as well as the lower temperature in the centre of the flow cross-section (comparable to the water phase). The literature speaks of pseudo film boiling, which can result in very low heat transfer coefficients and thus in very high tube wall temperatures, the same as at subcritical pressure.

The measurements in the BENSON laboratory were therefore performed at very small pressure increments of as low as only 1 to 3 bar in the pressure range close to the critical pressure, as shown in Figure 3, a calculated temperature profile in the pressure range close to the critical pressure.

Figure 4 shows the basic flow diagram for the BENSON test facility in Erlangen. It has a thermal pressuriser dimensioned such that volume changes on evaporation or condensation in the test rig are fully compensated. Pressure remains extremely stable in system operation on evaporation either in the heater or in the test tube as well as on condensation in the downstream spray condenser. The maximum pressure fluctuations are ± 0.1 bar. This is an

**Figure 4. Flow scheme of BENSON test facility, with thermal pressuriser**





Examples of power plants using BENSON low mass flux vertically-tubed evaporator systems: Lausward CCGT cogen plant, Germany (above); Longview coal fired plant, USA (below); Lagisza circulating fluidised bed plant, Poland (right)



absolutely necessary condition to enable the establishment of reliable steady-state heat transfer measurements in the pressure range close to the critical pressure.

The extensive investigations performed to date on a large number of standard and optimised rifled tubes using very small pressure steps have shown that tube geometry has a critical effect on heat transfer behaviour in the pressure range close to the critical pressure. For example, a greater rib height as well as optimisation of the lead angle results in an increase in the operating pressure at which the changeover from dryout to the departure from nucleate boiling occurs. In a standard rifled tube, DNB can be observed already at 175 bar, while this changeover to DNB does not take place until over 200 bar in an optimised rifled tube at the same boundary conditions. This is also associated with an improvement in heat transfer, ie, the tube wall temperatures established after the boiling crisis are significantly lower. The departure from nucleate boiling cannot be prevented on approaching the critical pressure in any tube type. However, the significant improvement in heat transfer in optimised rifled tubes enables reliable boiler design even at low mass flow rates and high heat loads.

Comparable results were also obtained in the supercritical pressure range. The above mentioned pseudo film boiling was observed in individual cases and especially at high heat loads in rifled tubes close to the critical pressure, between 220 and 230 bar, where the rifling geometry again has a critical effect on heat transfer behaviour. As applies for pressures close to the critical pressure below 220 bar, optimisation of the rib geometry decreases the pressure range above 220 bar at which pseudo film boiling occurs at all. Furthermore, the heat loads resulting in pseudo film boiling are significantly higher than in standard rifled tubes. Here as well, the optimised tubes again exhibit a significant overall improvement in heat transfer, ie, the tube wall temperatures established in the pseudo film boiling regime are significantly lower than in standard rifled tubes.

Manufacturers outside the BENSON licence also operate test stands for conducting heat transfer measurements. Some of these are of relatively simple construction and forgo a thermal pressuriser, presumably out of cost considerations. In such test stands, a piston pump is typically used to pump the fluid through a test heat exchange tube, and a throttle valve configured downstream of the tube is used to set the pressure. The test setups with this configuration are not suitable for heat transfer measurements in the pressure range close to the critical pressure, as the lack of an expansion tank or pressuriser subjects them to pressure fluctuations that exceed the requirement for the small pressure steps in the tests described above. Steady-state boundary

conditions, especially a constant pressure, cannot be set, thus preventing any reliable and reproducible measurements due to the sensitivity of the heat transfer behaviour in the pressure range close to the critical pressure.

Publications show that the operators of such test stands are attempting to verify the effect of the rifling geometry on heat transfer behaviour in their boiler tubes using CFD calculations. However, there are a number of restrictions, as noted in the following paragraphs.

Single-phase turbulent flow can in part be modeled by CFD with great accuracy with regard to the pressure and velocity fields. The turbulence models and wall functions required for this have been sufficiently researched as a function of the respective application.

In contrast, modelling capabilities for 2-phase flows with phase change and energy transport are much more limited, as the physical properties of such flows cannot be mathematically described with sufficient accuracy. The insufficient accuracy in some cases is due to a lack of detailed knowledge of various boiling mechanisms that are still under investigation worldwide. The applicability of the physical calculation models is heavily restricted, or they manifest weaknesses, especially in 3-dimensional modeling. This is further compounded by the fact that the small length and time scales in boiling phenomena require enormous computing capacity.

2-phase water/steam flows exhibit a high degree of complexity, which depends on a large number of interacting physical effects:

- momentum transfer – drag, lift;
- turbulence – bubble-inducing turbulence, turbulent wall functions;
- bubbles: coalescence and breakup, condensation, evaporation, wall boiling.

The Euler–Euler model with interpenetration of two continua is most frequently used for calculating 2-phase flows. In this model, the equations of conservation of mass, momentum and energy are applied, the values of which are weighted by their corresponding volume fractions. This representation requires special terms to ensure the interdependence of the respective physical properties. These are based on analytical expressions derived from various correlations that are heavily dependent on geometry. Additional source terms result for phase changes such as those due to a heated wall at which water is heated to boiling. These must also be accounted for by suitable physical modeling in the respective equations. It is therefore essential to validate the models for the specific application under consideration on the basis of conclusive test results. However, this represents a significant challenge even for academic studies concerning only individual effects. This is due to the enormous requirements placed on the instrumentation to enable the

achievement of sufficient accuracy for the parameters to be monitored at high pressure and high temperatures, such as in boiling phenomena. Average values for cross sections are insufficient for validation of the respective models.

### Successful market introduction

In summary, it can be stated that a large number of projects incorporating vertical-tube evaporators and low mass flux have been constructed and commissioned by various BENSON licensees, which can be regarded as successful market introduction of the BENSON low mass flux design.

References for once-through evaporator heat exchange surfaces with low mass flux and a positive flow characteristic are available only from BENSON licensees.

Measurements of heat transfer and pressure drop require a test facility with a thermal pressuriser, especially in the pressure range close to the critical pressure.

Computational fluid dynamics calculations are not suitable for describing 2-phase flows with phase change and energy transport with sufficient accuracy and replacing missing measurements.

Only the database available under the BENSON licence is based on measurements with small pressure steps, especially in the pressure range close to the critical pressure and for all tube types. This forms the basis for the design for reliable operation of the evaporator heat exchange surfaces for the BENSON licensees.

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