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 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/(sm²) 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.

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

![Figure 1. Overview of heat transfer and pressure drop investigations on the BENSON test facility, Erlangen, Germany, since 1975](image-url)
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 heated tubes with a geometry typical for vertically configured dynamic instabilities in vertically configured simulations.1,2 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.3 The first new construction project was the supercritical boiler for the Longview project, which was handed over to the customer in 2011.4 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 Jinhushan plant, commissioned in early 2009.5 Vertical tubing with low mass flux was also deployed in supercritical plants with circulating fluidised beds. The Lagiszsa,
plant was commissioned and handed over to the customer in early 2009. 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 with 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/(sm²) 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
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
modeling. This is further compounded by
the fact that the small length and time scales
in boiling phenomena require enormous
computing capacity.

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 vertical
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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