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Tube Swirler Inserts – Development Status

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Tube swirler inserts were developed for the evaporator heating surfaces of once-through boilers with a firing system. The improvement of the internal heat transfer has been shown in extensive measurements. Application of the swirler inserts is not limited to the power industry. Any heat transmission process might benefit from the new technology, especially in case of two-phase flow. The inserts can be introduced into smooth tubes of any steel grade.

Keywords: Benson boiler, Coils, Heat transfer improvement, Rifled tubing, Twisted tapes, Two phase flow

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1 Motivation for Development

Various boiler concepts were investigated in subprojects of the EU-sponsored Thermie and AD700 R&D projects headed by VGB PowerTech e.V. [1]. The objective was to construct a supercritical coal-fired demonstration power plant that would achieve an efficiency rate of up to 55 % at approx. 400 MW.

In modern supercritical boilers, competition is primarily between the evaporator concepts with spiral tubing with smooth tubes and vertical tubing with optimized rifled tubes [2]. Because of the increased supercritical main steam parameters of 700 °C at 350 bar the outlet temperature from the evaporator also increases with an equivalent release of heat from the flue gas. Use of materials T23 and T24 with roughly 2.6 % chromium already implemented in evaporators would significantly limit the possible fuel spectrum in a 700-°C power plant. Only coals with very high ash-softening temperatures are used in order to limit the steam outlet temperature from a compact evaporator to approx. 500 °C.

A switch to the group of steels with 9 – 12 % chromium content at least in parts of the evaporator was discussed in the above projects and was considered a possible option. However, the cold drawing process for producing rifled tubes is limited to materials with a maximum chromium content of roughly 5 %. The group of steels with 9 – 12 % chromium content is thus excluded for use as an evaporator tube in a Benson boiler with a low mass flux design – because rifled tubing is a prerequisite for this kind of evaporator tubing in a pulverized coal-fired boiler.

Following welding, the 9 – 12 % chromium steels require post-weld heat treatment, which is difficult to implement in a furnace with spiral tubing. The welds do not usually lie in a plane, and the necessary welds in the corners of the furnace result in a large number of points requiring heat treatment. For vertical tubing, the welds are always in a single plane and the tubing does not have to be routed around the corners in the furnace, resulting in advantages for the Benson low mass flux design, especially regarding post-weld heat treatment.

For this reason, development was started for the production of a tube swirler insert in the context of R&D activities in the Benson license. The rotation of the fluid on the inside is to be generated by an insert and not by the cold-drawn rifling. The initial purpose of the development was to produce a smooth tube with inserts providing very similar thermohydraulic characteristics to those of a highly optimized rifled tube. Tests in the Benson test rig have shown that with optimized rifled tubing the design mass flux in an evaporator can be reduced to 50 % compared to a smooth tube for identical material temperatures.

In a rifled tube the boiling crisis does not take place until steam quality is > 0.9. The reason is the swirl flow generated by the spiral ribs inside the tubes. Differences in centrifugal force separate the water from the steam fraction and force the water to the tube wall. This maintains tube wall wetting up to high steam qualities, resulting in high flow velocities even at the location of the boiling crisis. This yields a good heat transfer with low wall temperatures, especially in case of two-phase flow.

In a so-called low mass flux design the pressure drop of the lower furnace tubing can be reduced, e.g., from 9 bar in an evaporator spiral with smooth tubes to roughly 2 bar in a vertically tubed evaporator with optimized rifled tubing. The reduction in mass flux and pressure drop also leads to a change in flow characteristic. The pressure drop due to friction is reduced relative to the hydrostatic pressure, changing the flow characteristic of the evaporator system to that of natural circulation. Mass flow deviations caused by changes in heat input are governed by the hydrostatic pres-

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sure drop. A higher heat input to a single tube results in an increase in mass flow through this tube. The increased outlet temperature caused by excessive heat input is thereby compensated to the major part. The evaporator concept with low mass flux using optimized rifled tubing and the thermohydraulic behavior has been described in a number of publications [3 – 8].

In many CFD (computational fluid dynamic) calculations, the geometry of the insert was defined such that a similar pressure drop and comparable internal heat transfer could be anticipated.

2 Insert Production

The key component for producing the inserts is what is known as the template shaft. Wires are introduced in the slots in the template shaft, and these are inserted in a smooth tube together with the shaft (Fig. 1).

The wires of the subsequent insert are guided by the winding head shown below to the template shaft and are clamped to the end face. If the template shaft is turned clockwise in the winding head, it automatically takes along the wires guided by the winding head. The smooth heat exchange tube, into which the template shaft moves together with the insert, is positioned at the end face of the winding head.

As soon as the shaft projects past the far end of the heat exchange tube, the rotation of the shaft is stopped. The wire clamp is loosened, and the shaft is then turned back slightly. When the shaft is turned back, the wires automatically stay in their position in the tube. As soon as the template shaft is again completely within the heat exchange tube, the projecting wires are welded to the end of the tube and cut off. The template shaft is then completely turned out of the heat exchange tube. The wires are also welded and then cut off on the end just ahead of the winding head.

Residual stresses cause the individual wires of the inserts to lie very securely against the inner wall of the tube. Further securing of the wires in the tubes is not necessary. Fig. 1 shows the process on turning the template shaft back. The finished insert in the tube can be seen in front of the template shaft. This relatively simple setup has been used to incorporate inserts in tubes of up to 12 m in length with an inside diameter of 25.4 mm.

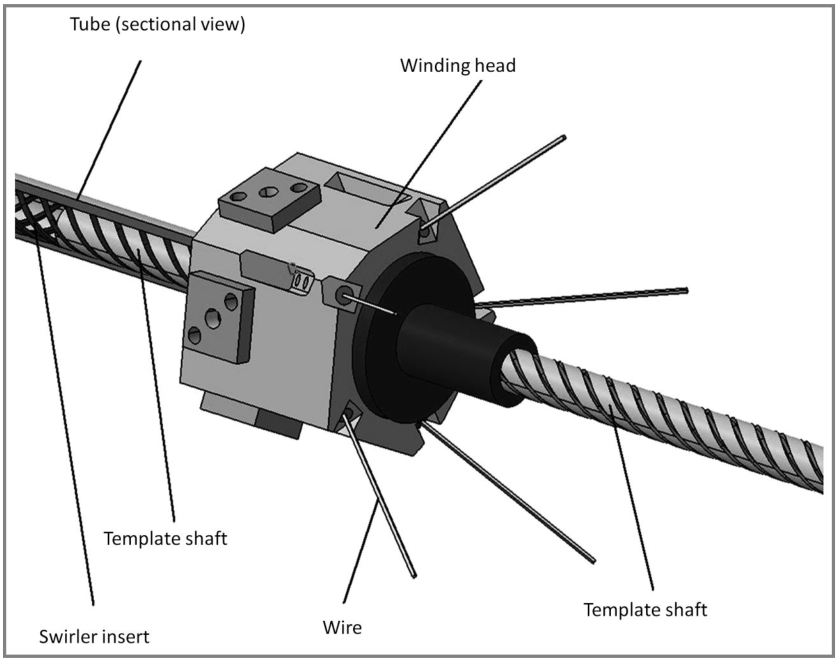

Figure 1. Template shaft, winding head, tube and swirler insert on turning back (5-wire inserts).

3 Results from Laboratory Tests

Since the mid-1970s, countless test series have been conducted in the Benson laboratory in Erlangen. Looking at the design data of the test rig as, e.g., a maximum pressure of 330 bar, maximum fluid temperature of 600 °C, a mass flow of up to 4 kg s^{-1} for a single tube and a heating capacity of 2000 kW, it is to our knowledge the world's largest test facility for measuring pressure drop and heat transfer in the two-phase regime [9, 10].

The test facility mainly comprises a water supply system, the object to be tested, a pressurizer and a cooling system (Fig. 2). In the water supply system, demineralized and de-aerated water or boiler feedwater to which chemicals have been added to obtain the required water chemistry is provided in a feedwater tank. This water is injected into the test loop by a piston pump. To minimize flow oscillations caused by the pump's six pistons, a damping vessel is installed in the pump discharge line.

The water is heated in a preheater and a main heater to establish the thermodynamic flow conditions required at the inlet to the test object. These coil-type heaters are designed for direct electric heating. The advantage of this heating method is that it allows precise control of the heat added to the fluid. This is especially important when developing heat transfer and pressure drop correlations. Experiments using other methods such as radiation heating are less suitable for these tasks, because a precise determination of fluid enthalpy or of actual heat input is more difficult.

After the fluid has passed through the main heater, it enters the test section, which is likewise equipped for direct electric heating, and where the flow and

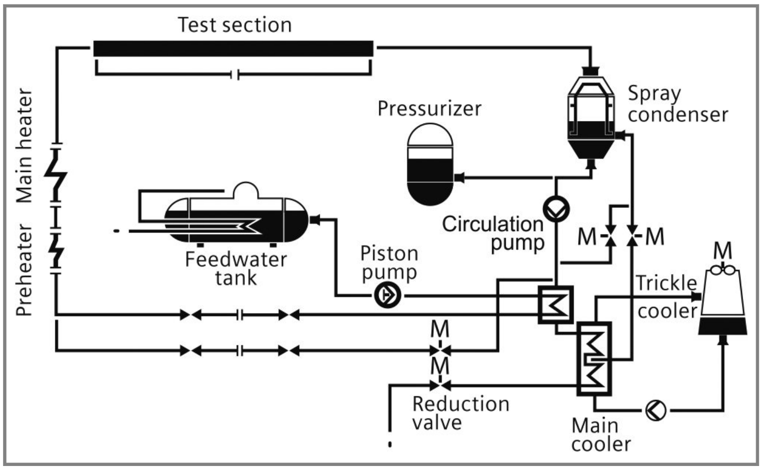

Figure 2. Benson test rig.

heat transfer conditions are simulated and monitored. Installed downstream of the test object is a spray-type condenser for condensing the steam fraction and subcooling the fluid. The subcooled fluid then passes to a circulation pump that recirculates part of the flow for cooling the spray condenser. Condenser cooling water is taken from the main flow immediately downstream of the pump and from the main cooler, which is supplied on its secondary side with water from a wet cooling tower (trickle cooler).

The system pressure is adjusted by a large thermal pressurizer and a throttling valve downstream of the test object. Assurance of a constant pressure is very important for studies performed near the critical pressure, because pressure fluctuations can affect heat transfer conditions in the test object.

The Benson test rig and the test object are instrumented in such a way that all relevant parameters like temperature, pressure and flow can be measured. Data acquisition and process visualization play a key role in recording and monitoring the individual experiments.

Inserts made by the method described above have been investigated in several laboratory test series. The first test series used an 8 m long smooth tube with an inside diameter of 25.4 mm and a 4-wire insert. Fig. 3 shows a piece of the 4-wire insert in a Plexiglas tube.

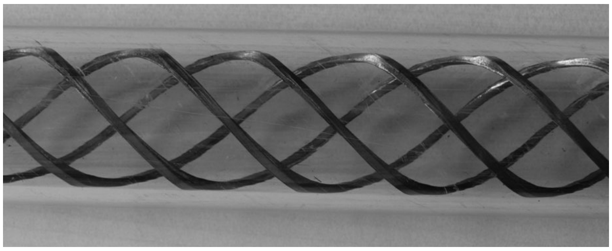

Figure 3. 4-wire insert installed in a Plexiglas tube for demonstration purposes.

A 5-wire insert was used in the second test series. In order to be able to use the already existing instrumentation, the insert was installed in the same smooth tube with 25.4 mm inside diameter and the entire test matrix was processed again. Fig. 4 shows the combinations of mass flux, heat flux and pressure for the tests. The entire enthalpy range of interest is investigated at all pressures. At subcritical pressures this means the enthalpy range between subcooling at the inlet, the occurrence of the boiling crisis (departure from nucleate boiling (DNB) or dryout), and the single-phase steam flow at the outlet. At supercritical pressures, a similar enthalpy range is studied throughout the entire pseudo-critical regime.

The key results of the heat transfer and pressure drop tests were that the 5-wire swirler insert installed in the smooth tube exhibits excellent heat transfer behavior that is nearly identical to an optimized rifled tube. This applies especially for typical operating conditions in a design with vertical tubes characterized by low mass flux. Fig. 5 shows a comparison of measured inner wall temperatures for the smooth tube with the 5-wire swirler insert with those from tests with an optimized rifled tube (RR19) just below the critical pressure. A sharp increase in the tube inner wall temperature results in a boiling crisis. Both the location of the boiling crisis as well as the wall temperatures measured subsequently in the so-called post-CHF (post-critical heat flux) area are nearly identical.

Fig. 6 shows the measured inner wall temperatures of a smooth tube (DB04) compared with the swirler insert measurements in a comparable mass flux range. Looking at the temperatures along the smooth tube with 300 $\mathrm{kW\,m^{-2}}$ heat flux, the boiling crisis DNB occurs slightly above an enthalpy of 1800 $\mathrm{kJ\,kg^{-1}}$, leading to an inside peak wall temperature of 570 °C. With the swirler insert and more than double the heat flux, the peak wall temperature downstream of the boiling crisis was measured at 470 °C. This shows the magnitude of improvement in heat transfer by using swirler inserts.

In addition, the tube friction factors in a smooth tube with swirler inserts were very close to the values for an optimized rifled tube. The two development goals with regard to thermohydraulic properties were fully achieved using the 5-wire inserts. Nevertheless, both, friction factors and inner heat transfer, can be further optimized as the shape of the wire as well as the lead angle can be varied in a much wider range than in internally rifled tubes.

4 Cutting, Bending and Internal Welding of the Insert

For possible use of the inserts in smooth tubes, such as in the evaporator heat exchange surfaces of a fired boiler, it

Mass flux [kg/m²s]	Heat flux [kW/m²]	Pressure [bar] 50	100	150	175	200	210	212.5	215	217.5	220	230
300	150											
	200	●	●	●			●	●	●	●		
	250								●	●		
	300						●	●			●	●
500	200											
	300	●	●	●			●	●	●	●		
	400	●	●	●	●	●	●	●	●	●	●	●
	500				●	●						●
750	300											
	400	●	●	●	●				●			
	500	●	●	●	●	●	●	●	●	●	●	●
	600					●	●	●	●	●	●	●
1000	300											
	400											
	500			●	●	●		●	●	●	●	●
	600			●	●	●	●	●	●	●	●	●
	700						●					
1500	500											
	600				●	●						
	700				●	●	●	●	●	●	●	●
	800				●	●	●	●	●	●	●	●
	900					●	●	●	●	●	●	●
2000	700					●	●	●	●	●	●	●
	800					●	●	●	●	●	●	●
	900					●	●	●	●	●	●	●
2500	800						●	●	●	●	●	●
	900					●	●	●	●	●	●	●
	1000					●	●	●	●	●	●	●

Figure 4. Test matrix.

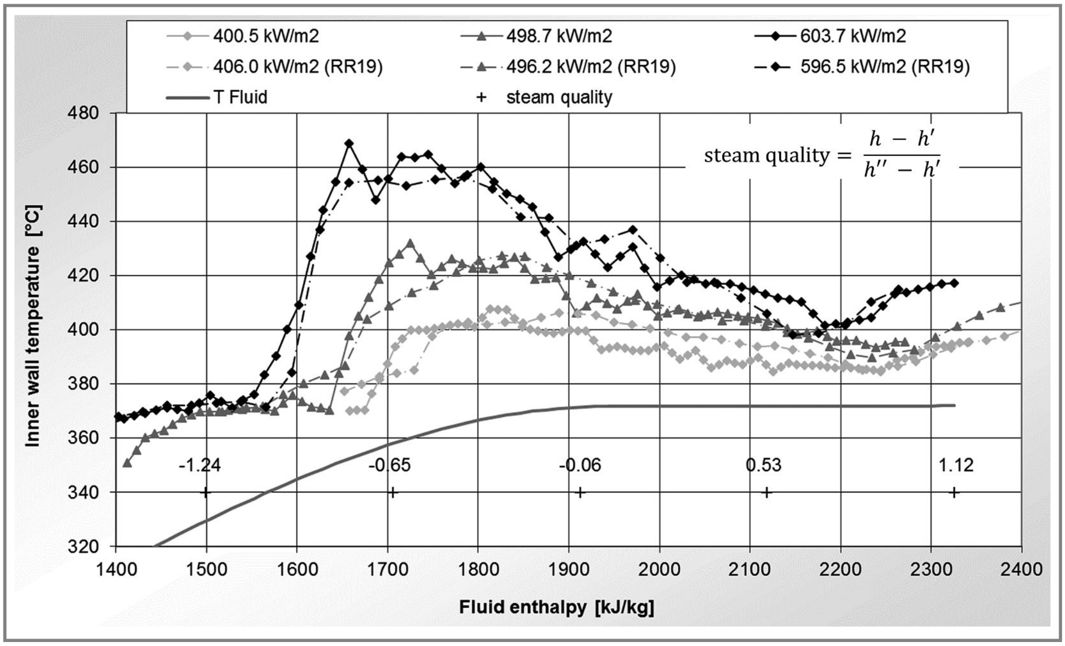

Figure 5. Comparison of measured inner wall temperatures for smooth tube with 5-wire swirler insert with those for an optimized rifled tube RR19 just below the critical pressure. Pressure 215 bar, mass flux 750 kg m^{-2}s^{-1}.

must be possible to bend the tubes or also to cut out a tube section from the evaporator wall and to replace it in the event of a necessary repair.

After a tube with a swirler insert was cut, some of the individual wires in an area up to a maximum of 15 cm from the cut edge had lost their positions. However, the wires were able to be easily moved back to their old position and fixed there by welding. Replacement of a defective tube section in a heat exchange surface would thus be possible with no difficulties. On bending the tubes, it proved that the

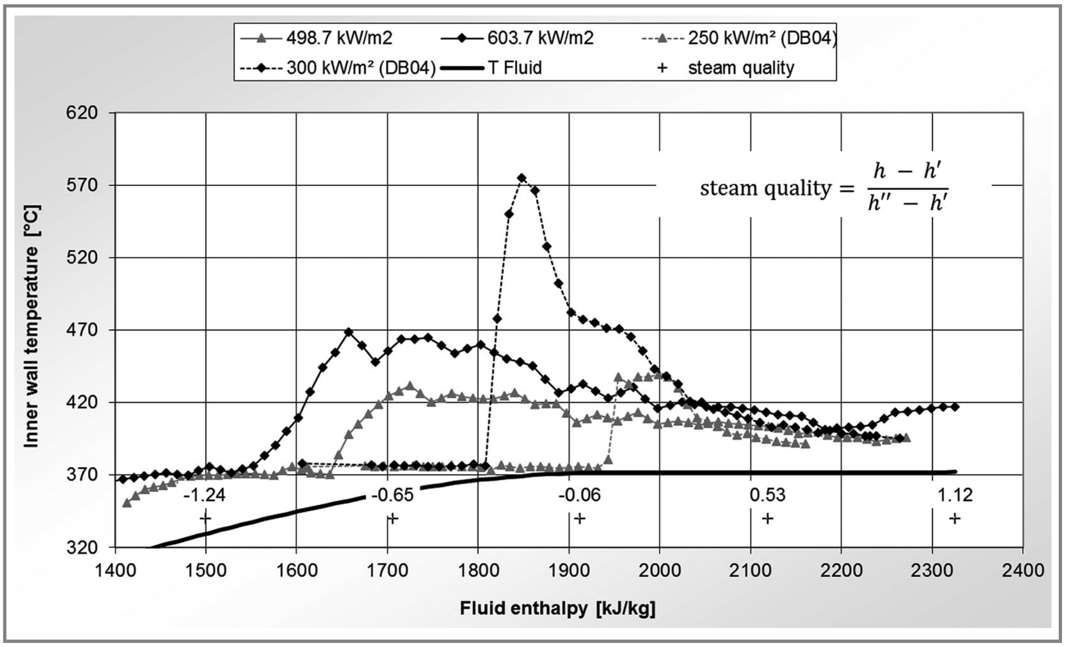

Figure 6. Comparison of measured inner wall temperatures for smooth tube with 5-wire swirler insert with those for a smooth tube (DB04) just below the critical pressure. Pressure 215 bar, mass flux 750 kg m^{-2}s^{-1} and 715 kg m^{-2}s^{-1} (DB04).

insert wires laid perfectly against the inside of the tube even for a small bend radius of 150 mm (just less than 4*D*), see Fig. 7.

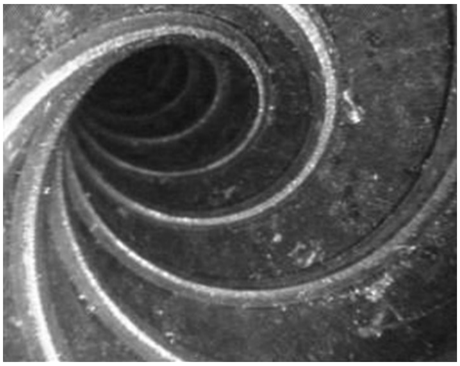

Figure 7. Insert in a tube bend.

To improve acceptance from potential customers, a procedure was developed with which the insert can be welded in the tube. The resistance welding method is used that is implemented in areas including automotive manufacturing. A lance for welding in the tube was developed and constructed based on the results obtained in preliminary tests (see Fig. 8). A hydraulic cylinder presses against the swirler insert on one inside and also presses the electrode against the insert wire on the opposite side. The pressing force can be adjusted via the pressure of the hydraulic fluid. The current is routed through the insulated copper lance.

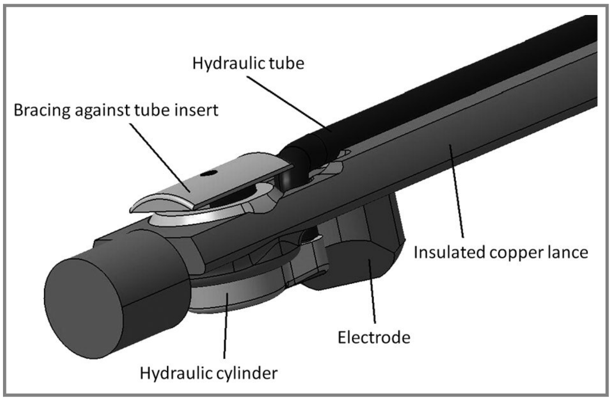

Figure 8. Welding lance (without insulation).

The welding lance described above was successfully used to make welds on the insert in the tube. Automatic positioning of the lance in the tube has not yet been developed, with the result that the lance had to be optically aligned in the weld tests. Further development of the internal welding process, which is only regarded as an option, was discontinued for commercial reasons.

5 Outlook – Applications Within and Outside the Power Plant Industry

Initial discussions were conducted with a manufacturer of rifled tubes for evaluation of the manufacturing process for an insert in comparison with cold-drawn rifled tubes. From the perspective of the tube manufacturer, it is not ruled out that the production of an insert may be more cost-effective than the cold-drawing process. The resulting freedom of material selection and the option of also using differing materials for the tube and insert was evaluated as positive.

The industrial manufacturing process for inserts is currently being investigated and evaluated regarding the costs in comparison with rifled tubes. The welding of the inserts in the tube that is seen as an option is not considered here.

As mentioned initially, development of the inserts was started because a steel with a chromium content of 9 – 12 % must presumably be used for the evaporator tubing in a boiler with a high-pressure steam temperature of 700 °C for the so-called Benson low mass flux design. A solution has been developed with the inserts which can be used to replace the cold-drawn rifling.

Development has now progressed to the point that, in the next step, a test heat exchange surface would have to be produced from smooth tubes with inserts and installed in a boiler. Such a test could demonstrate that the inserts provide the necessary tube cooling in actual power plant operation and that internal welding can be permanently foregone.

Unfortunately, the market has changed radically over the last decade. The 700-°C projects are no longer under consideration in Europe and only Japan, China and India still have ongoing R&D activities in this area. It is uncertain whether such a project will ever be implemented on an industrial scale.

Implementation of the smooth tubes with inserts described in the article could be expedient in solar tower power plants with direct evaporation. Stainless steels are used for the evaporator heat exchange surfaces due to the extremely high heat fluxes. The inserts significantly improve internal heat transfer, especially in the two-phase zone, and reduce the material temperature of the heat exchange tube. Unfortunately, however, solar tower power plants have not yet achieved a significant market volume, and one has the impression that photovoltaics are overtaking in the solar energy field.

It is currently being tested and investigated whether there are applications, such as in the chemical industry or in the petrochemical industry, that could benefit from a significant improvement in internal heat transfer through the use of inserts. Internal heat transfer is especially improved where flow is two-phase.

Development of the inserts is at a critical point. The originally planned implementation in the evaporator of a fired boiler is becoming increasingly less probable. Future development to the point of production on an industrial scale will only take place if further implementation possibilities are forthcoming.

Symbols used

h	[kJ kg^{-1}]	enthalpy
h'	[kJ kg^{-1}]	enthalpy of saturated water
h"	[kJ kg^{-1}]	enthalpy of saturated steam

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