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The Power Industry's View of Past, Present, and Future Two-Phase Flow Testing

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Since 1974, Siemens' Power Generation Group (KWU) has been operating a high-pressure two-phase flow test loop—called the Benson test rig—which offers a range of operating conditions that is unique in the world (1 to 330 bar, 20 to 600°C, and 0 to 2 MW electric heating power). The 25th anniversary of the first tests performed at this test rig presents a good occasion not only for reviewing the past, but also for contemplating the future of two-phase flow experiments.

The past was characterized by integral and separate effect tests for power generation using nuclear, fossil, and renewable energy sources as well as for process industries. This article will present examples demonstrating the flexible and broad range of applications for the Benson test rig. The results of the tests have been used to develop algorithms for implementation in computer programs and also for validating such programs.

Usually these computer programs—so-called analysis tools—are used for analyzing systems or components. From an analyst's point of view, two-phase flow experiments serve either to verify global flow conditions or to supply inputs such as boundary conditions and material laws and/or initial conditions for the analysis tools. An advanced way of making sure that all available knowledge can be input into the analysis tools is to collect and store it in a program system from which it can be called up, whenever required, according to the task in hand. Siemens' KWU Group has started developing such a system. Apart from integral tests conducted for new power plants, future two-phase flow experiments will probably focus on expanding this program system's database.

Siemens' Power Generation Group (KWU) has been operating the Benson test rig—a test rig that is unique in the world due to its wide range of operating conditions—in one of its accredited laboratories since 1974. The test rig's 25th anniversary is an exceptional event for any test facility and thus offers a good occasion for reviewing the past and contemplating the future. As the name of the test rig implies, its main purpose is to investigate topics associated with the design, operation, or further

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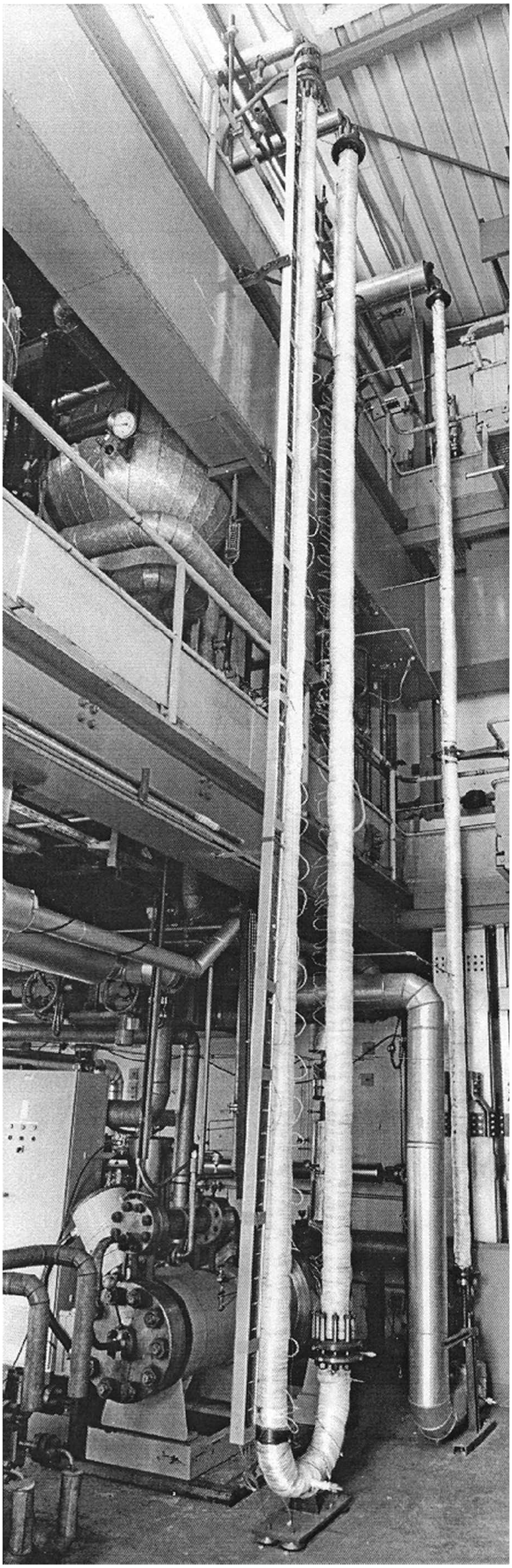

Figure 1 Benson test rig.

development of Benson boilers, i.e., fossil-fired once-through boilers. However, the test facility's flexibility also enables it to be used for other applications in the nuclear and renewable power industries as well as process industries. Some of the investigations have been performed in cooperation with universities and research institutes. Based on our 25 years of industrial experience concerning two-phase flow tests and applications, the following should also throw light on the purpose of future two-phase flow testing.

BENSON TEST RIG

Figure 1 shows a section of the Benson test rig, and Figure 2 its flow diagram. Its range of operating conditions is unique throughout the world:

Pressure	1–330 bar
Temperature	20–600 °C
Power	0–2 MW
Mass flow	0–28 kg/s

The main sections of the test facility comprise a water treatment system including injection and recirculation systems, the object to be tested, a pressurizer, and a cooling system. Demineralized and deaerated water is injected into the test loop by a piston pump. A damping vessel is installed directly downstream of the piston pump to prevent oscillations. The test rig can be operated in the recirculation mode for high flow rates or in the once-through mode for low flow rates. To maintain a constant water chemistry, a certain amount of the water is exchanged in the recirculation mode.

The water is heated by being passed through one main heater and up to two preheaters. Depending on the size of the object being tested, heating can take the form of direct electric heating—i.e., the wall of the test object acts as a resistor—or indirect heating via wires mounted on or in the wall. Since the preheater as well

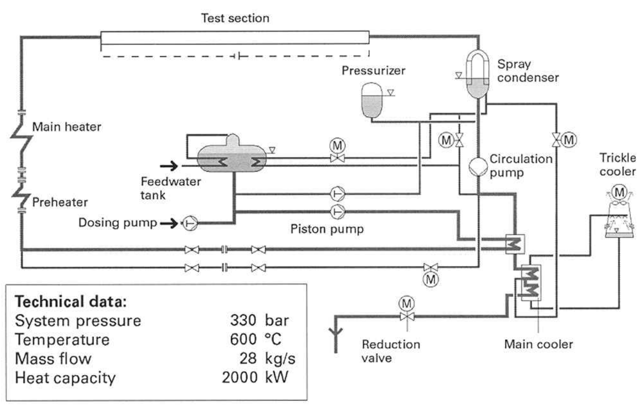

Figure 2 Benson test rig, flow diagram.

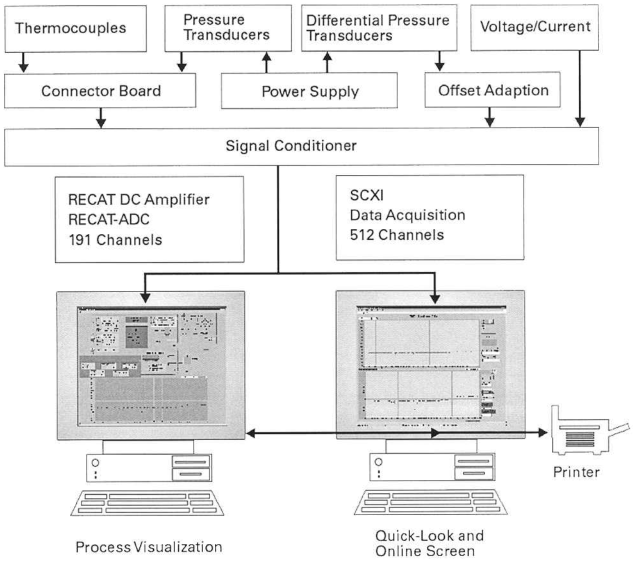

Figure 3 Data acquisition and visualization.

as the test object are electrically heated, it is possible to establish any enthalpy at the inlet and outlet of the test section via energy balances. Heat losses are included in this balance despite the fact that they are very low due to the insulation, which is over 50 mm thick. A spray-type condenser installed downstream of the test object condenses and subcools the water.

System pressure is adjusted by a large thermal pressurizer and a throttling valve downstream of the test object. Assurance of a constant pressure during steady-state tests is very important, especially near the critical point, because pressure oscillations affect heat transfer conditions in the test object. With this combination of valve and pressurizer it is also possible to perform tests with predefined pressure gradients.

The Benson test rig as well as the test object are instrumented in such a way that all relevant parameters are measured. The data acquisition and visualization equipment has been constantly adapted to the state of the art over the past 25 years. Figure 3 shows the structure of the present data acquisition and visualization systems. Visualization on two screens, as shown in Figure 3, ensures that the operator has a clear picture at all times of current thermal-hydraulic conditions as well as measured parameters such as the temperatures in the wall of the test object.

DESCRIPTION AND CHARACTERIZATION OF TYPICAL RESEARCH WORK

Regardless of the specific types of experiments that have been performed at the Benson test rig, all of the tests can basically be broken down into the following two categories:

1. Integral tests. The aim of these tests is to verify the functional behavior of components such as heat exchangers, or to develop measuring equipment.
2. Separate effect tests. The aim of these tests is to investigate separate two-phase flow effects. They can be subdivided into two groups:
   a. Stand-alone tests. These tests are interesting in their own right, such as investigations of erosion corrosion.
   b. Boundary tests. The aim of these tests is to investigate flow behavior in or around structures. The information gained from the tests is used in component analyses. In many cases, this information comprises boundary or initial conditions and material laws for analysis tools such as finite-element (FE) programs, which need heat transfer coefficients as inputs for temperature distribution calculations.

Integral Tests

Examples of integral tests are functional tests carried out on a safety condenser (SACO) and tests performed to develop a compact wet steam measuring system.

In the case of the SACO, the aim of the experiments was to determine the heat exchange characteristic of the component which had been developed for the next generation of pressurized water reactors (PWR). The design of the SACO is based on the idea of using an almost passive-decay heat removal system for the event of a loss of heat sink on the secondary side. Figure 4 shows how the SACO could be installed downstream of a steam generator. In the event of a secondary-side loss of the heat sink, the steam would be condensed by evaporating water on the tertiary side. As the temperature differences are expected to be high, heat fluxes of up to 600 kW/m^2 would occur at mass fluxes of less than 40 kg/m^2 s. The pressure would be near the containment pressure and thus in the range 1.35–5 bar. The SACO is designed as a tubular heat exchanger with condensation taking place inside the tubes. Heat transfer was investigated in two phases. In the first phase, only the tertiary side was considered by electrically heating tube. In the second phase, a section (3 × 3 tube bundle) of the SACO—shown on the right-hand side of Figure 4—was built into the Benson test rig. The secondary-side steam was provided from the Benson test rig itself. The height of all connecting pipes was scaled 1:1 in order to consider elevation effects. During the test campaign, heat exchange characteristics as well as transient behavior were investigated.

The main result of these tests was that the heat exchange behavior of the SACO was verified. For example, Figure 5 shows the exchangeable heat flow for

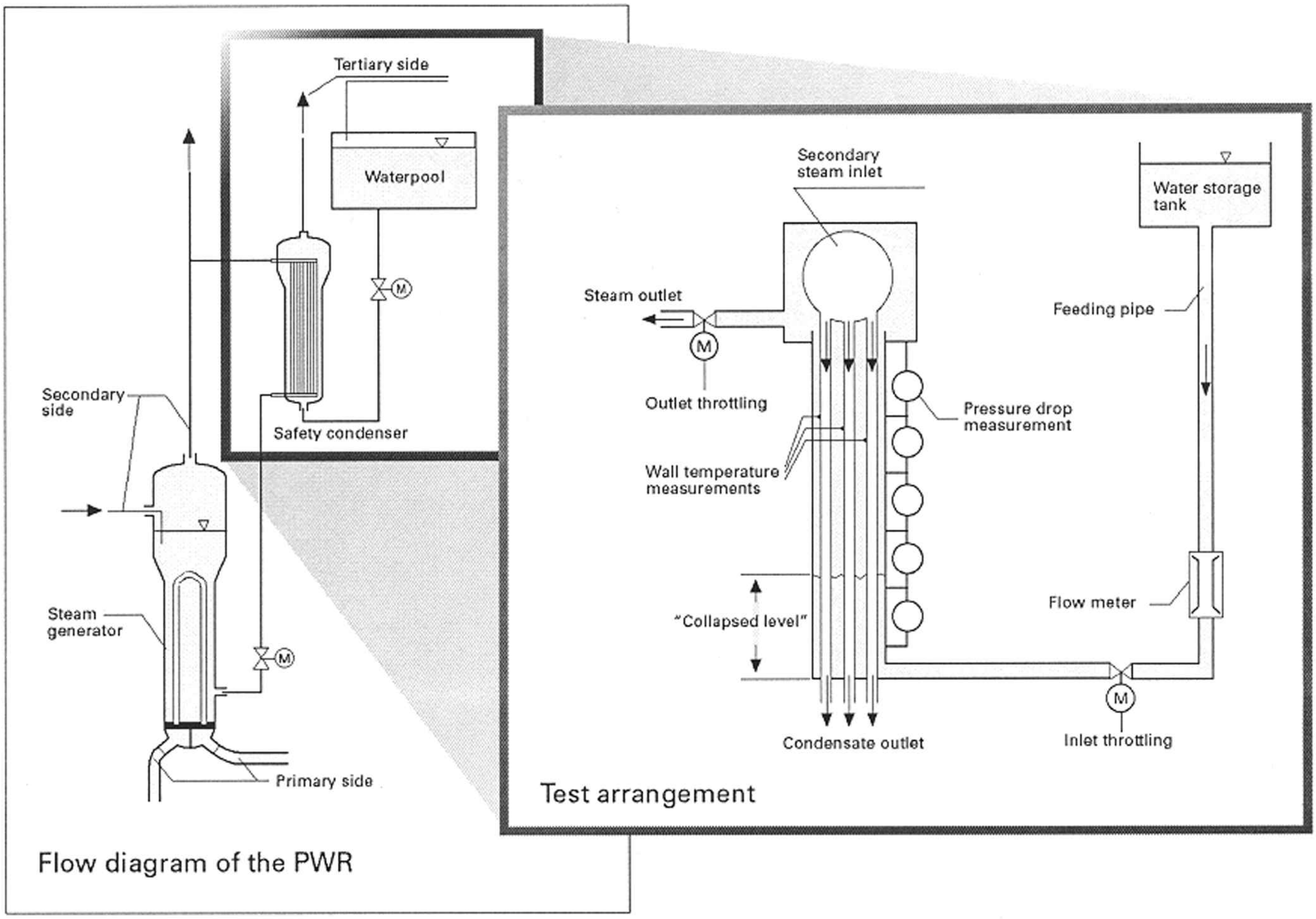

Figure 4 Investigation on the integration of a safety condenser (SACO) to the secondary side of a PWR.

steady-state conditions. One interesting effect of the heat exchange characteristic is that the exchangeable heat flow is independent of the pressure on the secondary side over a wide range. An explanation for this is that the tertiary side dominates the heat exchange process. As the tests showed, the boiling crisis occurs at high steam qualities. In the postdryout region, heat transfer is low compared to the regions with nucleate and subcooled boiling, and thus the contribution to heat exchange is also small. The experiments also verified that the critical steam quality, which is the steam quality at which the boiling crisis occurs, depends mainly on the mass flux and is largely independent of the heat flux. In the case of a higher secondary pressure, the temperature difference between the secondary and tertiary sides is larger, and thus the heat flux in the nucleate boiling region is also higher than when secondary-side pressure is low. This means that, for high secondary-side pressures, a smaller heat exchange surface area is needed to reach the critical steam quality. In each case, the same amount of heat is exchanged at similar mass fluxes, since only the area involved prior to the boiling crisis is relevant for the heat exchange process and the magnitude of heat exchange is similar at approximately constant critical heat fluxes (see also [1]).

Another typical kind of integral test is for calibrating measuring equipment. For example, Siemens' KWU Group developed a mass flow and steam quality measuring device—shown schematically in Figure 6—which was then calibrated in the Benson test rig. This system consists of a venturi tube, a one-beam gamma densitometer, a temperature sensor, a differential pressure sensor, and an absolute pressure sensor. The flow through the venturi creates a pressure drop that is proportional to the square root of the mass flow for a certain density and is measured by the gamma densitometer. The flow through the venturi leads to such a high degree of homogenization that a one-beam gamma densitometer can be used. Based on the measured temperature and pressure, the properties of the fluid are taken into account. The calibration measurements were used to develop an algorithm for calculating the steam quality, the mass flow, and the fluid enthalpy (see also [2]).

Use of such a device installed at the end of the boiler section to control the feedwater of a fossil-fired once-through steam generator was compared to the method presently employed and was found to have certain

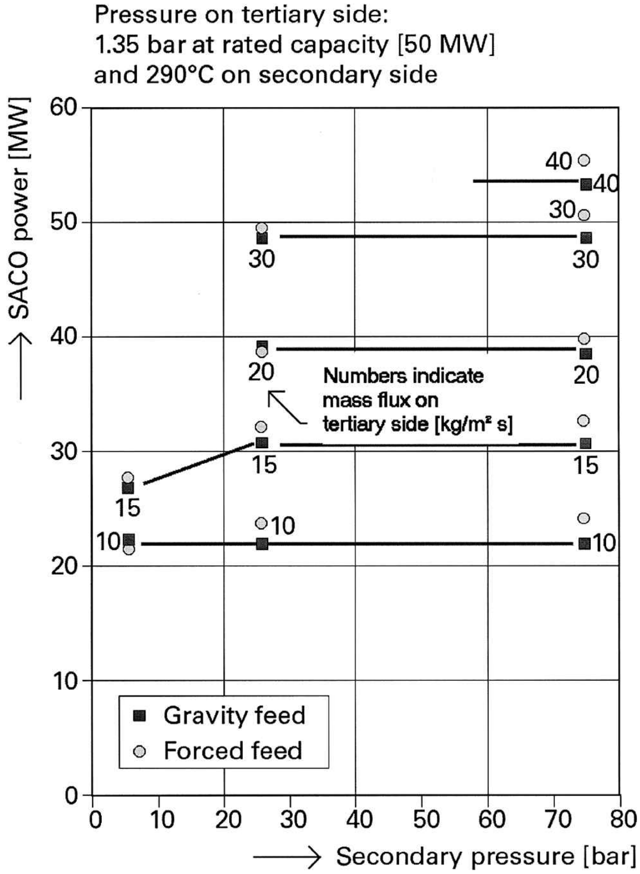

Figure 5 SACO power with gravity and forced feed.

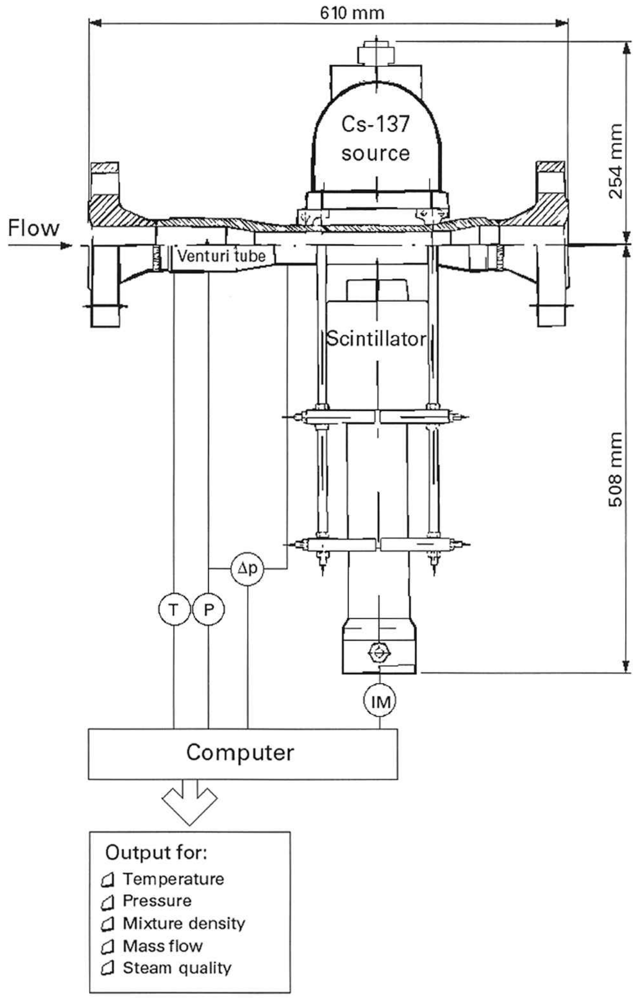

Figure 6 Wet steam measuring system.

advantages. Up until now, it has been common practice to measure temperature and pressure downstream of the first superheater. However, measurement of the enthalpy at the outlet of the boiler results in faster response, meaning that the effects of changes in firing or transient heating effects are detected earlier. This has a positive effect on the service life of the high-pressure components installed downstream of the boiler section.

Stand-Alone Tests

The aim of stand-alone tests is not to develop a database which can be used to supply boundary conditions for component analyses. Instead, the results of these tests are interesting just in their own right. For example, tests have been performed at the Benson test rig to investigate erosion corrosion, a corrosion mechanism that is greatly influenced by flow behavior. This type of corrosion occurs only if the wall is wetted—for example, in the case of single-phase flow or two-phase flow with bubbly, stratified, or annular flow patterns—and if the corrosion resistance of the wall is dependent upon the formation of a protective oxide layer. The conditions promoting this kind of corrosion are so complex that it is not possible to describe them in a way that enables the two-phase flow conditions to be investigated separately from the metallurgical and chemical effects (e.g., as mass transfer coefficients). Hence, the reductions in wall thickness were measured directly. For this purpose, various objects were tested in the Benson test rig (plates, tubes, bends, reducers, and increasers). Wall thinning was measured for conditions based on various flows, temperatures, water chemistries, and materials. Using this data—a couple of examples are shown in Figure 7, where the experimental determined wall thickness reduction due to erosion corrosion is plotted as the wall thinning measured in mm/year versus some typical parameters—a computer program (called WATHEC) was developed which is employed in power plant design to avoid significant erosion corrosion. For existing power plants, it is also possible to identify locations at which the wall thickness should be measured, meaning that the scope of in-service inspections can be reduced (see also [3–5]).

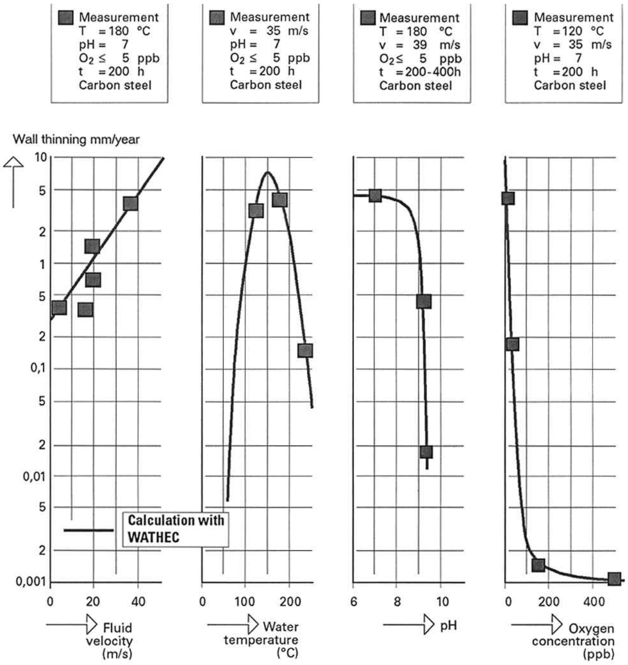

Figure 7 Wall thinning due to erosion corrosion (effect of thermal hydraulics and water chemistry).

Boundary Tests

Most of the tests performed at the Benson test rig have been part of component analyses for the power and process industries. In the following, examples will be presented of individual boundary tests carried out for the fossil, nuclear, and solar power industries as well as for a process industry in order to demonstrate the flexibility of the Benson test rig and to explain typical boundary test applications.

Waterwall Tubes for Benson Boilers

Benson boilers are once-through steam generators. The steam is generated in tubes which are welded together to form gas-tight walls. These walls surround the combustion chamber where the fuel is fired. In designing the combustion chamber, both the flue-gas side and the water side have to be taken into consideration. The steam quality at the outlet of a once-through boiler is higher than 1; i.e., the steam is superheated, with the consequence that all of the flow patterns shown in Figure 8 as well as the boiling crisis occur in the boiler section. Subcooled boiling also typically occurs, this is indicated in Figure 8 by two different definitions of the steam quality ($\dot{x}$ and $\dot{x}_{\text{mass}}$). From the design point of view this is the energy-balanced steam quality $\dot{x}$—in the following called just steam quality—which is defined as the ratio of the difference between the cross section-averaged enthalpy minus the saturation enthalpy and the heat of evaporation. The mass-balanced steam quality $\dot{x}_{\text{mass}}$ is defined as the ratio of the actual steam to the sum of steam and water flow. The mass-balanced steam quality together with the energy-balanced steam quality give a hint as to where a nonequilibrium condition may occur in a cross section. For the design of boilers, it is essential to know where the boiling crisis is located and to have information on heat transfer at this position. It is generally an advantage if the boiling crisis occurs at high steam qualities and thus at a high position in the waterwall that is relatively far away from the burners. Another advantage of high critical steam qualities is the relatively good heat transfer behavior due to the high steam velocities. In view of the relevance of heat transfer conditions in waterwall tubes, a variety of different

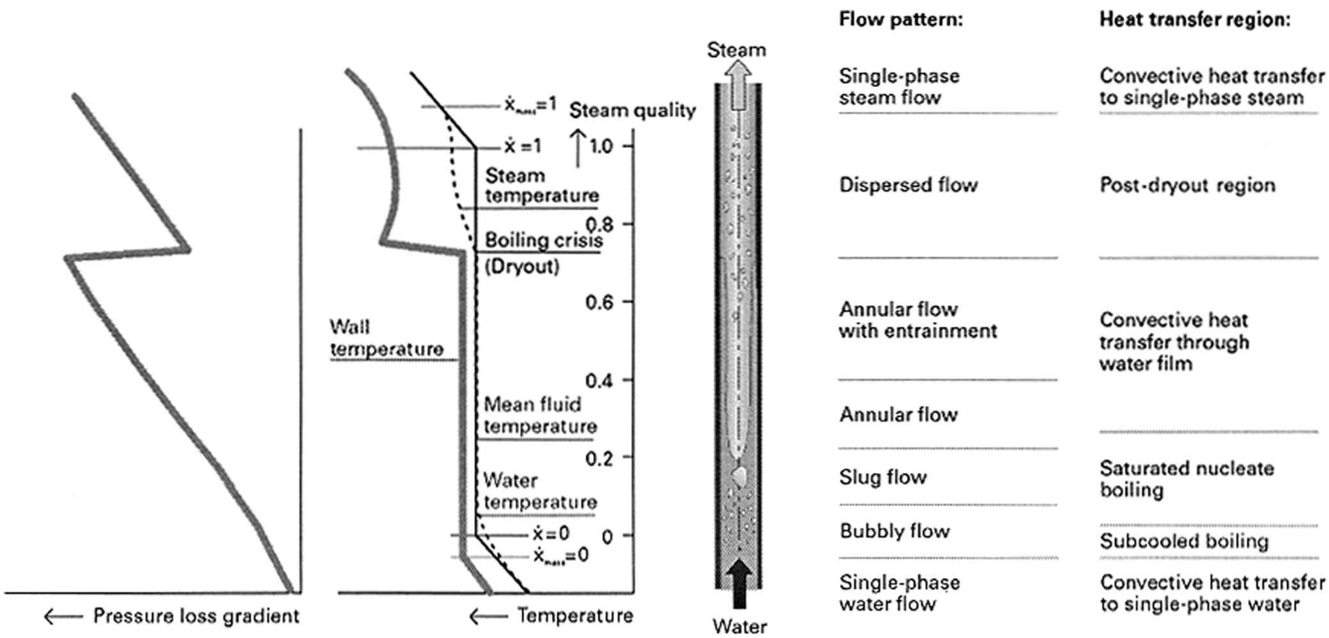

Figure 8 Wall temperature and pressure loss in an uniformly heated, vertical, smooth evaporator tube.

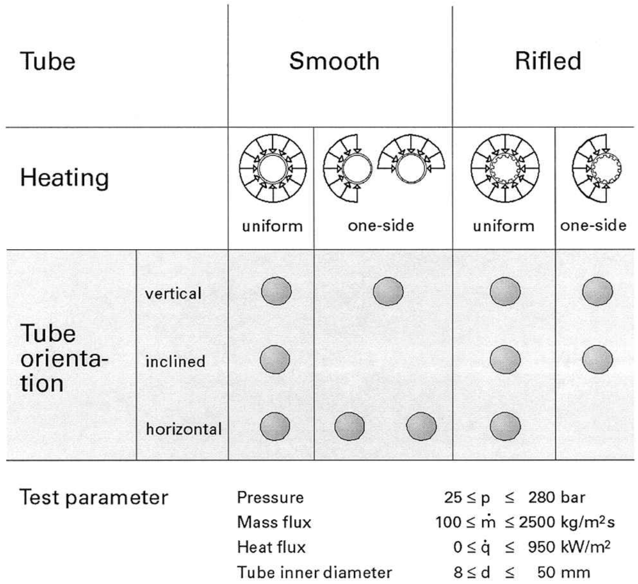

Figure 9 Test matrix for heat transfer and pressure drop investigations.

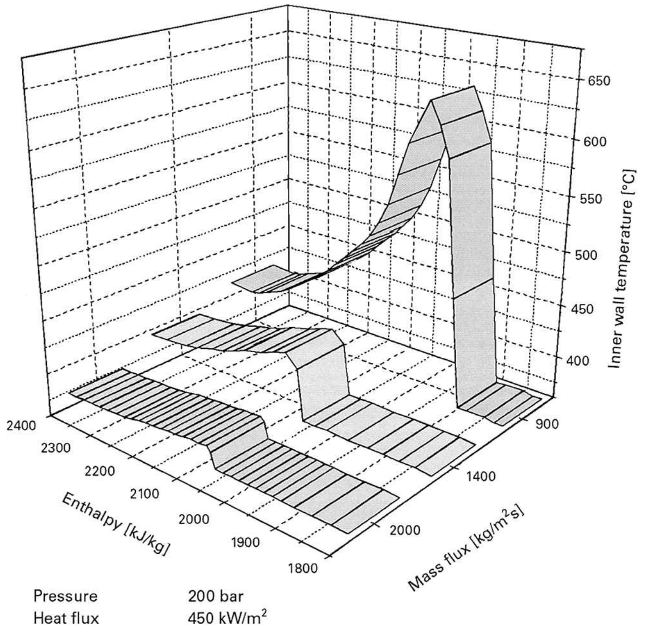

Figure 10 Effect of mass flux on the inner wall temperature of a smooth tube.

measurements have been performed in the Benson test rig. The main parameters of these tests are summarized in Figure 9. Different types of tubes were installed in the Benson test rig downstream of the heater so that the inlet steam quality could be varied. The electrical resistance of their walls was employed for heating the tubes. In some of the tests, the wall thickness was reduced over half of the tube circumference to simulate nonuniform heating. Pressure drops as well as wall temperatures were measured for different flow conditions. Using the results of these measurements, algorithms were developed which are being applied in steam generator design.

As an example taken from the database, Figure 10 shows the influence of the mass flux on the inner wall temperature. At low mass fluxes, the boiling crisis occurs at lower steam qualities and the waterwall temperatures are high. In the case of 900 kg/m^2 s, they would be much higher than the creep temperature of typical waterwall materials. For this reason, mass fluxes for 200 bar in the range between 1,400 and 2,000 kg/m^2 s are required. The tubes have to be installed at an inclination of approximately 30° because the size of the combustion chamber is governed by the design of the flue-gas side. This inclination requires supporting structures in order to avoid excessive bending stresses in the tubes. The waterwall tubes can only be installed in a vertical position if rifled tubes are used. The enhanced heat transfer behavior of rifled tubes is demonstrated by Figure 11, which shows the inner wall temperatures of two uniformly heated tubes, one smooth and one rifled. Although flow conditions are similar, the boiling crisis occurs in the rifled tube at a much higher steam quality than in the smooth tube. The reason for this effect is the swirl induced by the rifle geometry. The corresponding centrifugal forces imparted to the liquid phase inside the tube are responsible for rewetting of the wall and thus for the high critical steam quality. More than 100,000 temperature measurements taken on smooth tubes and 150,000 on rifled tubes presently form the basis for heat transfer correlations which, together with correlations for pressure drop, are key elements of design and analysis tools for Benson boilers. These tools include, for example, dynamic programs for analyzing startup and shutdown processes, and FE programs for calculating stresses and temperatures in waterwalls (see also [6–10]).

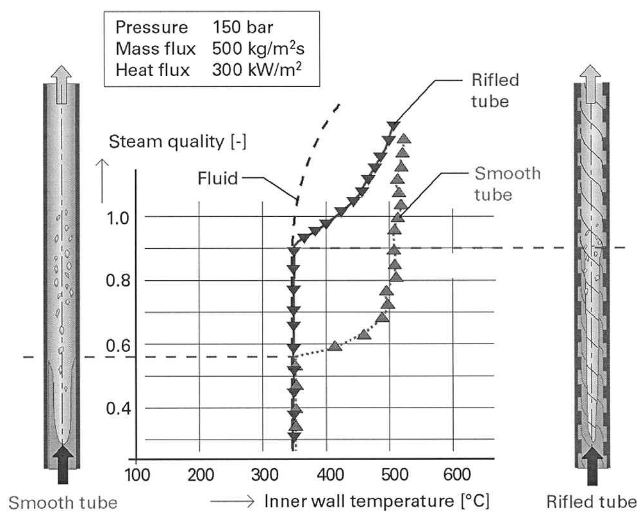

Figure 11 Wall temperatures in smooth and rifled tubes.

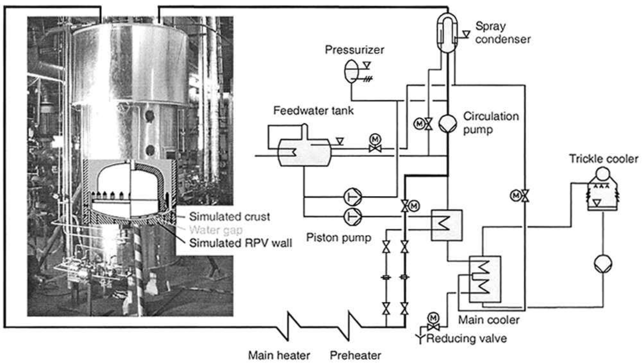

Figure 12 Test setup heat removal during the accident at TMI-2.

Heat Transfer between a Debris Crust and the Reactor Pressure Vessel Wall

During the Three Mile Island-2 (TMI-2) accident, the core of the reactor was partly melted. The molten debris penetrated into the lower plenum. Contrary to most assumptions, subsequent inspections revealed that the wall of the reactor pressure vessel (RPV) showed no signs of melting. This discovery could not be explained by the existing reactor safety codes. One main question was how large the maximum removable heat would have been if a gap between the debris crust and the RPV wall had been filled with water still present in the vessel. In a joint research program headed by the German Society for Reactor Safety (GRS), Siemens' KWU Group investigated the heat transfer conditions in such a gap. For this purpose a vessel was built and integrated into the Benson test rig as shown in Figure 12. The lower part of the vessel had a spherical shape, similar to the bottom head of the RPV. In order to simulate the debris crust, a heating element was mounted in the vessel, this element being movable in order to vary the gap width. Figure 13 shows the measured critical heat fluxes. They

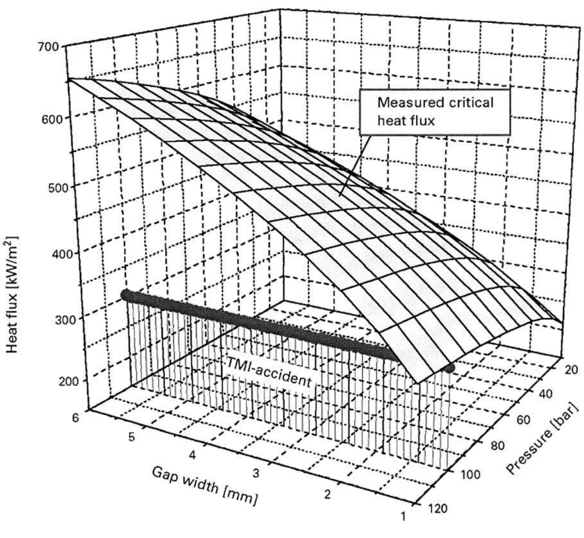

Figure 13 Validation of the heat removal from the molten debris during the TMI-2 accident.

are lower than the corresponding heat fluxes during the TMI-2 accident. Although a detailed analysis of the TMI-2 accident would be very complex, comparison of the heat fluxes gives a rough explanation of why the RPV retained its structural integrity. In order to obtain a deeper understanding of the accident and to transfer the new knowledge about heat transfer behavior in the gap to safety analyses for existing plants, it is possible to use an algorithm based on the results of these tests to describe the heat transfer boundary conditions (see also [11]).

Heat Transfer in Solar Farm Absorber Tubes

Among the various concepts for utilizing solar energy, solar thermal power generation in solar farms is the most widely used. At present, only farms employing thermal oil in absorber tubes to generate steam in a separate heat exchanger are in operation. As this thermal oil limits the maximum process temperatures and is also difficult to handle, new process concepts are under development to generate the steam directly in the absorber tubes. These processes are shown schematically in Figure 14. They are to be tested at Plata Forma Solar in Almeria (Spain). In a step preceding this development, the heat transfer conditions were investigated in the Benson test rig as part of a joint research project headed by the German Aerospace Research Establishment. The flow diagram of these tests is given in Figure 15, along with a picture showing the tubes in front of the building of the Benson test rig. Various tube geometries as well as heat fluxes and flow conditions were tested. Pressure drops and temperatures were measured. As an example, Figure 16 shows the inner wall temperatures. The results of these tests have been used to develop algorithms used in design studies for the solar power industry. One specific feature requiring investigation is deformation of the tubes due to nonuniform heating in order to avoid positioning outside of the focus of the mirrors or destruction of the surrounding glass insulation. Performing these kinds of investigations with an FE program requires heat transfer coefficients as boundary conditions which can be selected using the results of the tests performed in the Benson test rig (see also [12]).

Pressure Drop Tests

In most of the tests conducted at the Benson test rig, temperatures and pressure drops were measured. The pressure drops are important for component design and analysis as well as heat transfer behavior. Based on knowledge about pressure drops it is possible, for example, to analyze mass flow distributions in piping

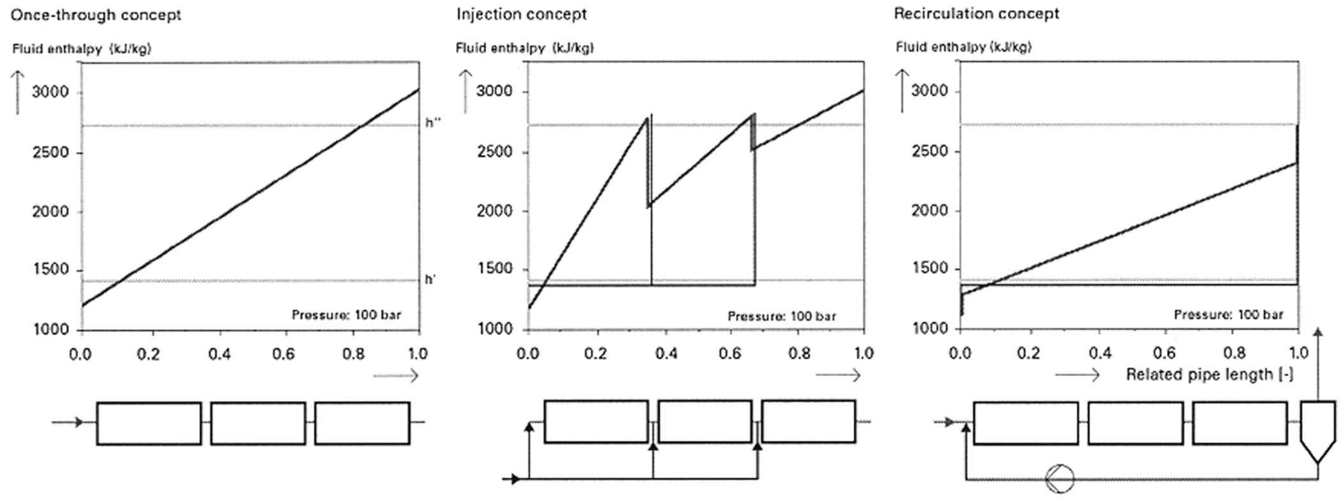

Figure 14 Concepts for direct solar steam generation.

networks or to size pumps, etc. Frictional pressure drops are typically represented as two-phase flow multipliers, which are dependent on flow conditions and geometry. For instance, it is interesting that the general characteristics of the two-phase flow multipliers for smooth and rifled tubes are different, as can be seen from Figure 17.

Pressure drops were the focus of a series of investigations of steam piping networks for the heavy-oil industry. These steam networks are used, especially in Venezuela, to inject steam into boreholes to increase output. As these networks are of a large size, a portion of the steam condenses inside the pipes. Many investigations were carried out to develop or validate algorithms for the pressure drop, including tests at the Benson test rig. Figure 18 shows the setup used for the test object and the main parameters of the test matrix. Figure 19 shows some selected results for a pipe bend, an inclined

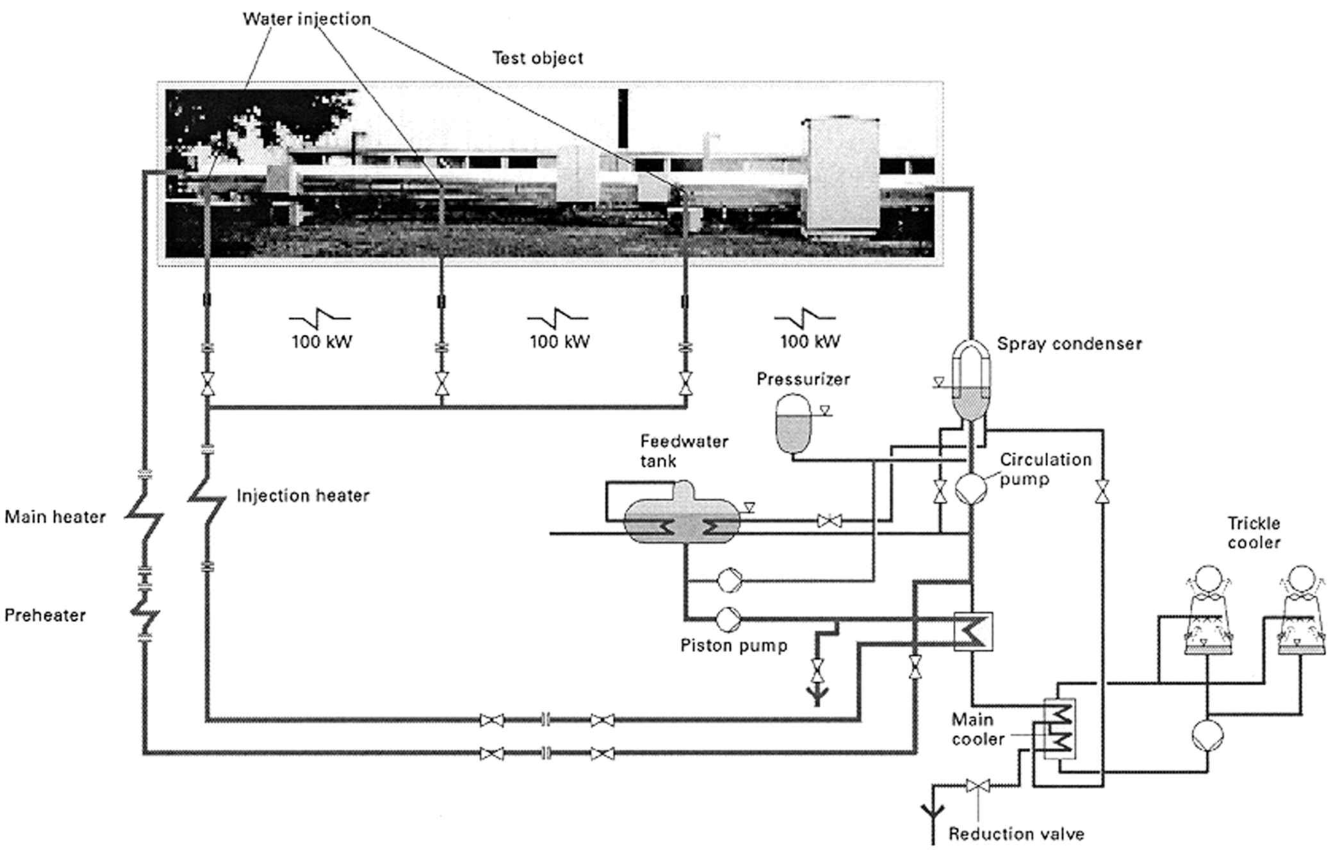

Figure 15 Test setup for direct steam generation investigations.

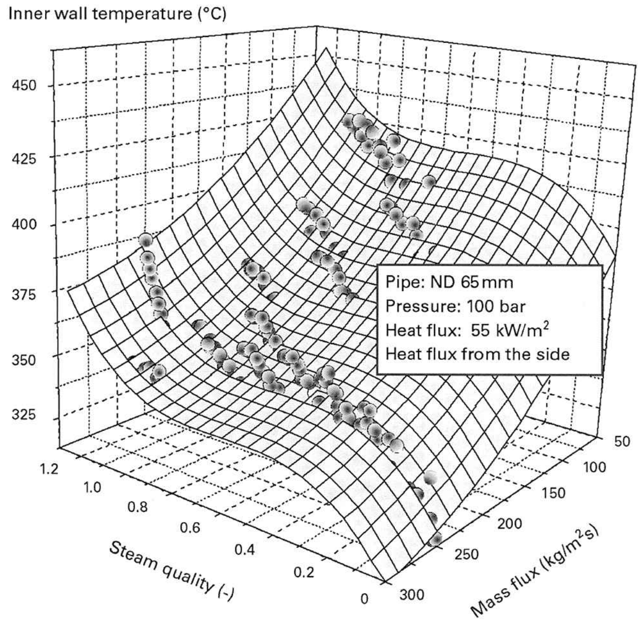

Figure 16 Temperatures at the upper side of the absorber tube.

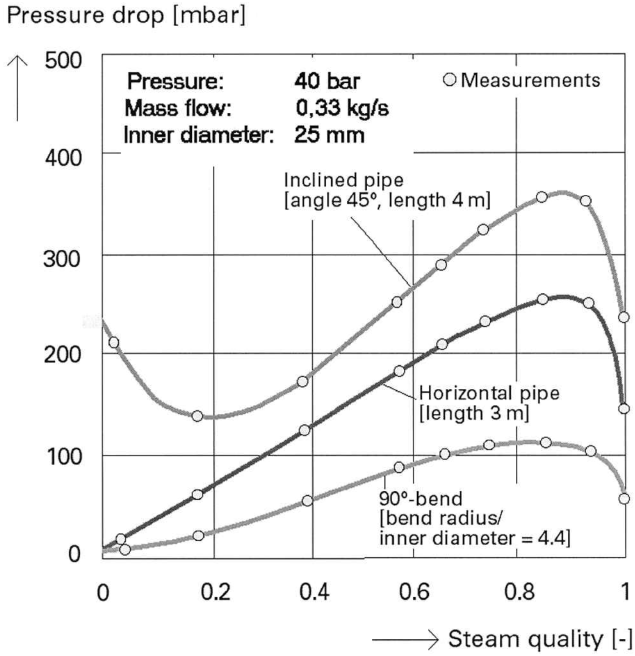

Figure 19 Two-phase flow pressure drop in various pipes.

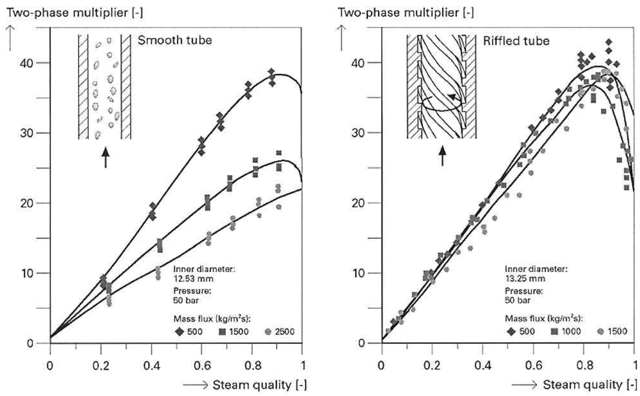

Figure 17 Effect of mass flux on pressure drop of smooth and rifled nonheated tubes.

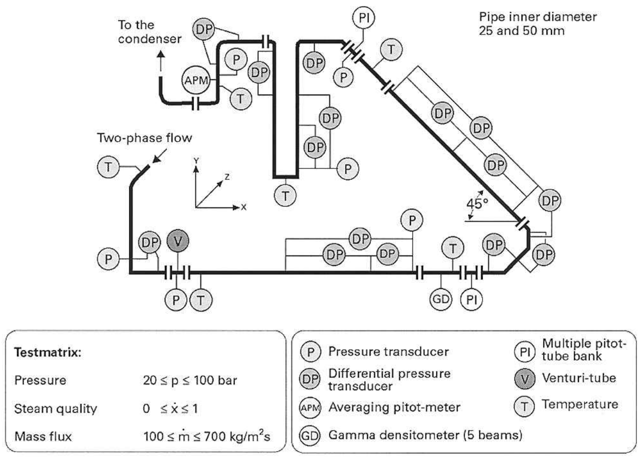

Figure 18 Test setup for pressure drop measurements in a pipe conveying wet steam.

pipe, and a horizontal pipe. The results were integrated into a simulation program which uses them mainly as boundary conditions (such as frictional pressure drops) or as material laws (such as for two-phase mixture densities) (see also [13]).

FUTURE PROSPECTS FOR TWO-PHASE FLOW EXPERIMENTS

From the point of view of the power industry, two-phase flow investigations are interesting as long as the steam cycle is an essential element of power generation. At present, most power plants comprise gas turbine plants combined with a steam cycle (combined-cycle plants), coal-fired plants, and nuclear plants. At combined-cycle plants, the steam cycle is of minor importance. The main requirements to be met by the steam cycle are ease of design and low-cost construction. At coal-fired and nuclear power plants, the steam cycles are very important. Especially in the case of new nuclear power plant designs, such as the EPR and the SWR 1000, it can be expected that integral tests will be necessary in order to verify the functional behavior of their new systems. These tests are dependent on the stage reached in the design process and it is difficult to foresee what kind of integral tests will have to be performed, and when. The situation is similar with regard to stand-alone tests. The requirements for new stand-alone tests will be governed by new developments in power plant water treatment, such as injection concepts for reducing ^{60}Co activity at nuclear power plants (see also [14]).

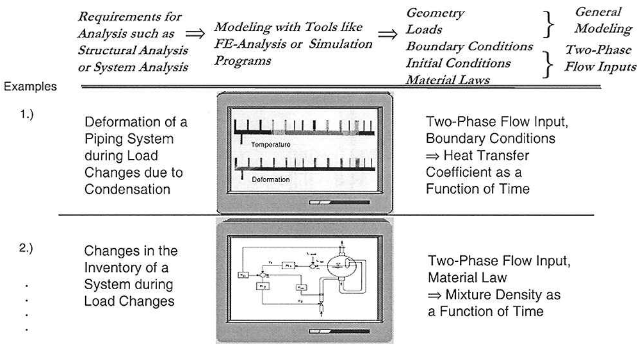

Figure 20 Engineering process for systems with two-phase flow.

Boundary tests are related to analysis tools and to the special conditions associated with certain applications. Hence, it can be expected that tests for waterwall tubes in, for example, once-through boilers will continue. From a general point of view, one can see two trends. First, competition in the power plant market is very strong, meaning that those who want to survive on this market will have to optimize their engineering processes. The second major trend is that the commercially available analysis tools will become more and more powerful and user-friendly. Looking at the engineering processes for systems in which two-phase flow occurs, one finds a structure of the kind shown schematically in Figure 20. The two main steps are general modeling, which includes description of the geometry and the loads, and two-phase flow input, which includes the description of material laws as well as initial and boundary conditions.

One example taken from an engineering process is analysis of the deformation of a header. For the analysis the header is a piping system with one big central tube and a large number of inlets and outlets. Under full-load conditions, it conveys superheated steam. During start-up, some of the inlets on the sides may be closed and the steam may be in a saturated state. This may result in condensation in some sections of the header. To investigate the deformation of such a system it is common practice to use finite-element programs. In a first step the temperature distribution in the header is calculated, which requires heat transfer coefficients—with and without phase change—as boundary condition, in order to determine the deformation in a second step with standard tools. The general procedure as well as temperature and deformation distribution for one time step are shown schematically in the middle of Figure 20. Another example is the estimation of the change in inventory in a drum boiler during load changes. These kinds of investigations are typically performed with simulation tools by solving the conservation equations for the mass, the momentum, and the energy. Therefore it is necessary to consider the structure of the boiler as well as the control system as it is shown schematically at the bottom of Figure 20. By considering the water–steam mixture in the boiler it is possible to neglect the two-phase flow frictional and the acceleration pressure drop. The remaining two-phase-flow input is the density of the two-phase mixture, which can be regarded as a material law. In both of the examples shown in Figure 20, two-phase-flow inputs are required. When one compares the modeling and input steps, it becomes clear that the modeling tools have reached a high standard which will become even higher in the future. The two-phase-flow input step is unique to each task in hand and is often very time-consuming and expensive. In many cases only a small portion of the knowledge available on two-phase flow is taken into consideration, something which also has an influence on quality.

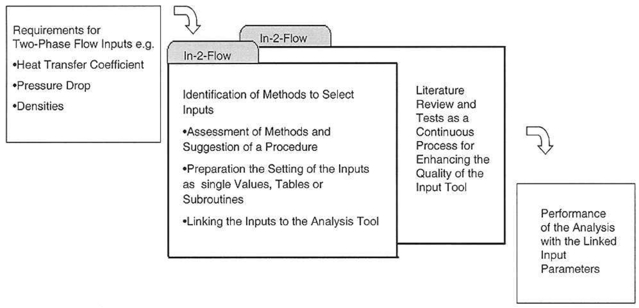

Figure 21 Automated two-phase flow input.

Siemens' KWU Group has started developing a program (called In-2-Flow) for automating the input step in such engineering processes, as outlined in Figure 21. This program will be employed in the general engineering process after specification of the modeling inputs and before performance of the analysis. It will automate the two-phase flow inputs. The first step is to assess the available methods. For tubes, for example, a large variety of different methods are available for calculating the void fraction, pressure drop, and heat transfer for various applications. Based on the most suitable method, it will then be possible to prepare the inputs in order to link them to the analysis tool. As can be seen from Figure 22, a database is the core component of such

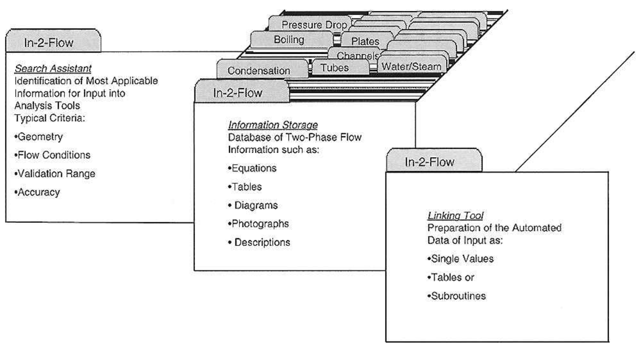

Figure 22 Main structure of the input tool.

a program. Although only heat transfer and pressure drop are mentioned in Figure 22, it is also planned for other two-phase flow data such as flow forces or leakage mass flows through small cracks (see also [15, 16]) to be considered as well. Relevant two-phase flow data will be collected in a database. For the purposes of this program, it will be necessary to store not only equations but also all additional information in order that a decision can be made. A search assistant will help the user find the most suitable method, although it might turn out that different methods should be used for different applications within the same simulation. Depending on the requirements of the simulation tool, it will be necessary to prepare the inputs as single values, tables, or subroutines. Initially, the knowledge base of this program will be taken from the available literature. Storing information in a database will also provide other advantages. One of these is that certain items of knowledge can be permanently retained. Also, a program of this kind can provide an overview of all of the knowledge that is available on a specific topic. This can be helpful for identifying areas in which there is a lack of information. Missing information can then be supplied by performing new boundary tests as part of a continuous process for enhancing the quality of the input tool.

CONCLUSION

Although a large variety of different two-phase flow experiments have been performed in the past, tests of this kind will still be needed in the future. These tests will be related to new developments in the fields of coal-fired and nuclear power generation and will take the form of integral tests or boundary tests for, e.g., waterwall applications. In addition, it can be expected that two-phase flow tests will also be performed in the future for enhancing the quality of a data input program currently under development at Siemens, the aim of this program being to automate the input of two-phase flow data in modern analysis tools.

REFERENCES

[1] Köhler, W., Herbst, O., and Kastner, W., Thermal-Hydraulic Behavior of a Safety Condenser, *Int. Conf. on New Trends in Nuclear System Thermohydraulic*, vol. 1, pp. 609–614, 1994.

[2] Kastner, W., Fischer, C., and Krätzer, W., Verbesserte Speisewasserregelung durch kompaktes Meßsystem zur Massenstrom- und Dampfgehaltsbestimmung, *BWK*, vol. 45, no. 12, pp. 510–514, 1993.

[3] Heitmann, H. G., and Kastner, W., Erosion-Corrosion in Water-Steam Cycles—Causes and Countermeasures, *VGB Kraftwerkstechnik*, vol. 62, no. 3, pp. 180–187, 1982.

[4] Kastner, W., Riedle, K., and Tratz, H., Experimental Investigations on Material Loss Due to Erosion-Corrosion, *VGB Kraftwerkstechnik*, vol. 64, no. 5, pp. 411–423, 1984.

[5] Kastner, W., Nopper, H., and Rößner, R., Vermeiden von Erosionskorrosionsschäden in Rohrleitungen, *3R Int.*, vol. 33, no. 8, pp. 423–428, 1994.

[6] Griem, H., Köhler, W., and Schmidt, H., Heat Transfer, Pressure Drop and Stresses in Evaporator Water Walls—From Experiment to Design, *VGB PowerTech*, vol. 79, no. 1, pp. 26–35, 1999.

[7] Köhler, W., Kefer, V., and Kastner, W., Heat Transfer in Vertical and Horizontal One-Side-Heated Evaporator Tubes, *Exp. Heat Transfer*, pp. 397–409, 1990.

[8] Kefer, V., Köhler, W., and Kastner, W., Critical Heat Flux (CHF) and Post-CHF Heat Transfer in Horizontal and Inclined Evaporator Tubes, *Int. J. Multiphase Flow*, vol. 15, no. 3, pp. 385–392, 1989.

[9] Köhler, W., and Kastner, W., Heat Transfer and Pressure Loss in Rifled Tubes, *8th Int. Heat Transfer Conf.*, vol. 6, pp. 2861–2865, 1986.

[10] Franke, J., Köhler, W., and Wittchow, E., Evaporator Designs for BENSON® Boilers—State of the Art and Latest Development Trends, *VGB Kraftwerkstechnik*, vol. 73, no. 4, pp. 307–315, 1993.

[11] Schmidt, H., Köhler, W., Herbst, O., and Krätzer, W., Experiments on Heat Removal in a Gap between Debris Crust and RPV Wall, *1st European-Japanese Two-Phase Flow Group Meeting*, 1998.

[12] Köhler, W., Herbst, O., and Kastner, W., Thermal Design of Solar Absorber Tubes with Direct Steam Generation, *8th Int. Symp. on Solar Thermal Concentrating Technologies*, 1996.

[13] Gonzales, M., Kastner, W., Künstle, K., Lezuo, A., Ostendorf, F. J., Reiter, K., Rodriguez, J., and Thelen, H., Upgrading of Venezuelan Crude Oil—Continuation of the Orinoco Feasibility Study within the Venezuelan/German Agreement (Annex III B), Final Report BMFT—Reference No. 03E-6400B, 1989.

[14] Nieder, D., Schneider-Kühnle, P., and Wolter, D., Introduction of Zinc Injection in NPP Biblis, Unit B, *VGB PowerTech*, no. 6, pp. 61–63, 1999.

[15] Kefer, V., and Kastner, W., Leckagen bei unterkritischen Rohrleitungsrissen—Ausströmraten und ihre Geräusche, *BWK*, vol. 39, no. 6, pp. 310–315, 1987.

[16] Kefer, V., Kastner, W., Westphal, F., John, H., Reimann, J., and Friedel, L., Vorhersagegenauigkeit von Modellen für Leckraten aus Rissen in druckführenden Komponenten, *DECHEMA—Monographien, Band 111, Fortschritte der Sicherheitstechnik II*, 1988.

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