CLASSIFICATION AND APPLICATIONS OF TWO-PHASE FLOW HEAT EXCHANGERS

F. MAYINGER

Lehrstuhl A für Thermodynamik
Technische Universität München
Munich, Federal Republic of Germany

ABSTRACT

Approximately 60% of heat exchangers in industrial use are working in a two-phase flow mode. They are used in the power and process industry as well as in air conditioning, in refrigerating, and in food production. Mostly the latent heat of evaporation of a vapour-liquid mixture is used to improve the transport capacity and also to enhance the heat transfer process.

After discussing different criteria and possibilities classifying two-phase flow heat exchangers, their design and application, some examples of modern design in heat exchangers with phase change, are presented. Finally thermo- and fluiddynamic phenomena are briefly discussed which have major influence on the design and the operational performance of two-phase flow heat exchangers.

The paper intends to give an introduction to the following lectures and papers dealing with the design of special two-phase flow heat exchangers and their heat transfer calculation in detail.

1. INTRODUCTION

The oldest two-phase flow heat exchanger used by mankind was certainly a cooking-vessel for preparing meal by boiling. One of the probably first two-phase flow heat exchanger for "public" use was proposed by Archimedes who invented a "steam-gun" for shooting bullets. Archimedes enclosed water in a tube, heated this water and water-vapour mixture, and finally untide the bullet being arrested on one side of the tube. This, perhaps, was the first industrialized use of a two-phase flow heat exchanger of military character proving the old Roman proverb: "War is the father of many things".

A little later Heron invented the "turning-sphere" which was fed by a boiler, one of the first two-phase flow heat exchanger design too. The boiler had, as fig.1 shows, the shape of a cooking-vessel of that time, i.e. no special design deliberations were performed. The steam produced in the "heat exchanger" - the cooking vessel - flowed via a short vertical pipe into a sphere which was put in rotation by the momentum of the steam jet leaving this sphere via two nozzles. Heat was added to the heat exchanger by a wood or coal fire.

In ancient Egypt boiling heat transfer is reported to have been used for producing alcohol via destilling wine. There is no drawing how this evaporator looked like. The use in food-production was the dominant application of two-phase flow heat exchangers until the beginning of the industrial age when James Watt invented his steam engine and chemical engineering started. From this time on a vehement development in two-phase flow heat exchangers began continuing until today.

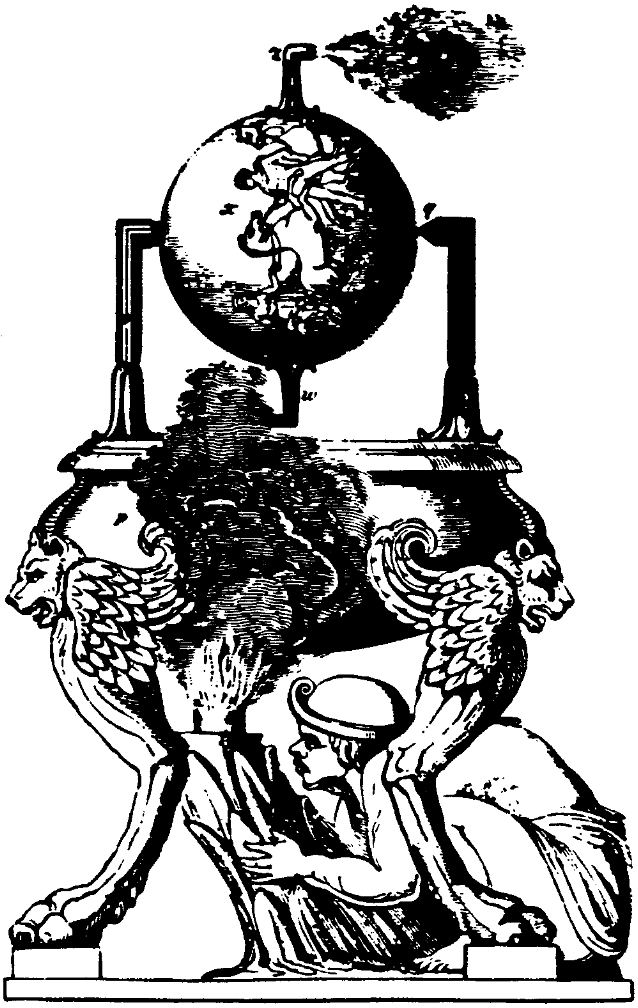

Fig.1: "Turning sphere", quoted by Hero of Alexandria, 120 b.c.

Mostly the benefits of phase change, namely the latent heat of evaporation and high heat flux densities were attractive to the designers of heat transport components but also the need to produce vapour, for example for a steam engine, or to separate a condensible component out of a gas mixture were reasons for engineers in the power- and process-industry to design and construct evaporators and condensers. In the chemical industry the function of an evaporator is to evaporize a liquid or to concentrate a solution by vaporizing part of the solvent. Sometimes this vaporizing goes to the point at which crystallization occurs. Then even a three-phase mixture may be present in such a heat exchanging apparatus. Vaporizing may start from rigid surfaces heated by a hot fluid from the other side or by radiation heat transfer but also on flexible surfaces, for example on a liquid-vapour interface, when a hot liquid is depressurized and flashing occurs.

Condensate may form from vapour in a number of different ways, usually there is filmwise condensation on a rigid wall. Dropwise condensation would allow much higher heat flux densities, but this is difficult to maintain contineously in heat exchangers. The vapour, however, can condense also out of a gas phase directly forming droplets suspended in the gas. Finally when vapour is brought directly into contact with a cold liquid, so-called direct contact condensation occurs.

For a systematic classification of two-phase flow heat exchangers however, we need a much more detailed view of the different possibilities of flow configurations, design aspects and application purposes.

2. CLASSIFICATION OF TWO-PHASE FLOW HEAT EXCHANGERS

Heat exchangers may be classified according to many different aspects and features. Shah /1/ proposed classifications according to the transfer processes, degree of surface compactness, construction features, flow arrangements, number of fluids, and heat transfer mechanisms. From the various possible criteria of classification, shown in a little different arrangement in fig.2, we will only discuss

Classification Criteria of
Heat Exchangers

I. Transfer Process
II. Construction
III. Flow Arrangement
IV. Heat Transfer Mechanisms
V. Number of Phases or Fluids
VI. Application

Fig.2: Classification Criteria for heat exchangers

the classification criterium according to heat transfer mechanisms, construction and application. Transfer processes according to Shah /1/ are direct contact or indirect contact for transporting the heat. In a direct contact type heat is transferred through direct contact between the hot and cold immiscible fluids, for example by condensing vapour in liquid. However, one of the fluids can also be a gas and the other one a very low vapour pressure liquid. A water cooling tower with forced or natural draft or flow is the most common application of direct contact heat exchangers. Here, however, we have to notify that more than 90% of the energy transfer is by virtue of mass transfer and heat transfer has much a minor mechanism.

In this paper, however, we shall mainly or only discuss indirect contact heat exchangers. Classifying heat exchangers in general according to their heat transfer mechanisms we can distinguish, as briefly outlined in fig.3, between single-phase convective heat transfer, heat transport due to phase change and heat transfer by radiation. According to this classification only the phase change mode of heat transfer is of interest here. Again, generally spoken, we would have to differ

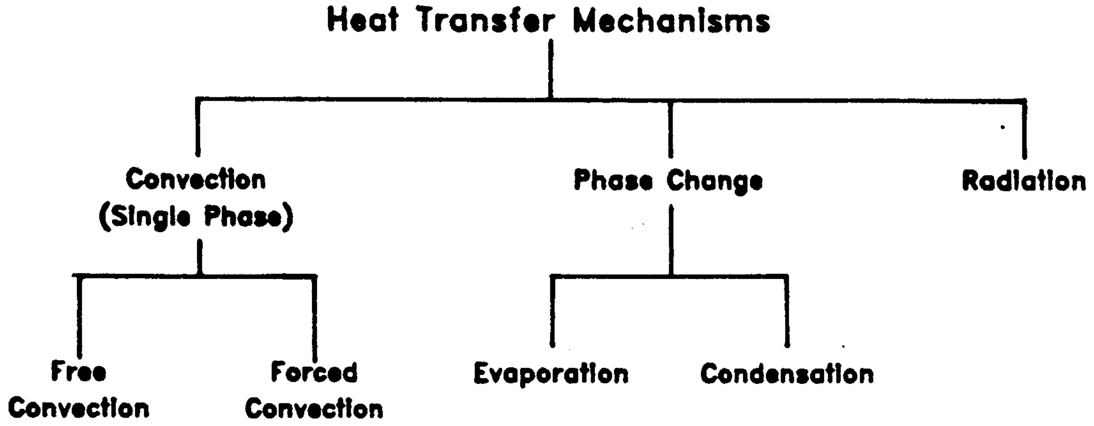

Fig.3: Classification of heat exchangers according to heat transfer mechanisms

between evaporation, condensation, sublimation, and de-sublimation. The later two heat transfer mechanisms, i.e. the direct change between gaseous and solid phase, play no role in technical and industrial heat transport.

However, also without phase change we may have a two-phase flow heat transfer mode. This is for example the case in fluidized beds where a mixture of gas and solid particles is transporting heat to or from a wall which may have the form of a cylinder or of a flat plate. This fluidized bed heat transfer mechanism became recently very timely in power engineering with the development of fluidized bed combustion. Tube bundles are there immersed in the fluidized bed of coal particles, ashes, and hot gas. Inside these tubes another type of two-phase flow exists, namely a liquid vapour mixture.

From a design point of view the classification of heat exchangers occurs much more detailed (fig.4). Many design concepts are used as well in two-phase

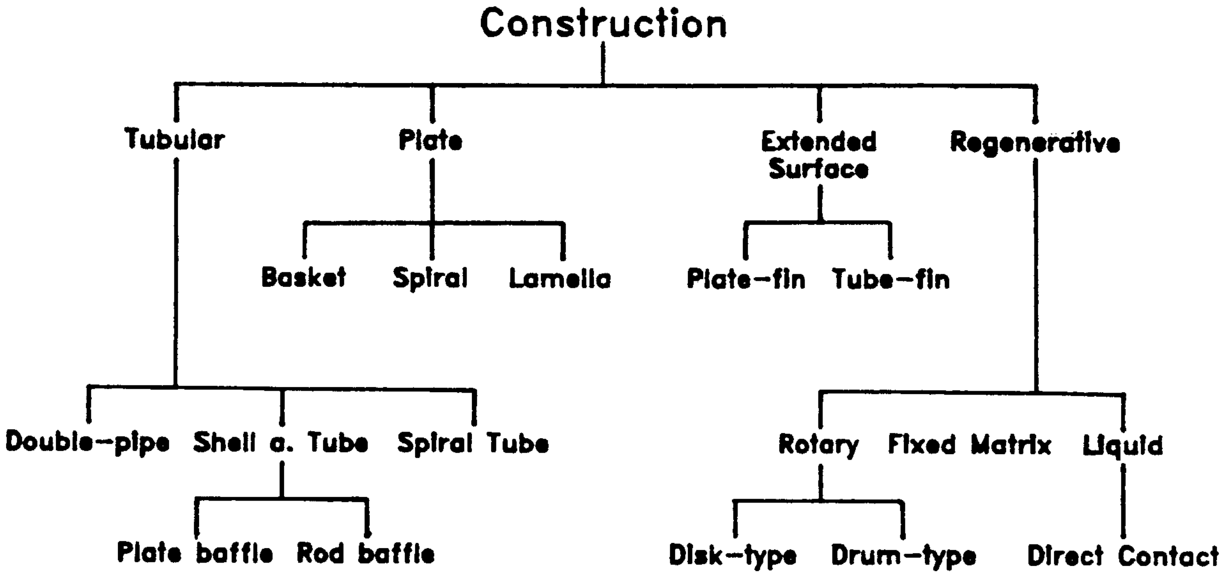

Fig.4: Classification of heat exchangers according to construction (R. Shah /1/)

mode as in single-phase one. From a pure geometrical point of view we can distinguish between a tubular- and a plate-design. However, we can also subdivide the walls transferring the heat in extended and in not-extended surfaces. As well known extended surfaces, like fins, are used in the tubular- as well as in the plate-arrangement, if the heat transfer coefficient is low.

Finally we have to consider whether the heat from the hotter fluid is transfered instantaneously to the colder one or whether it is stored for a while before it can heat up the colder fluid. Heat exchangers with this storage step in between are called regenerators. Two-phase flow heat exchangers are very rarely operated in a regenerative mode.

Two-phase flow heat exchangers are of tubular- and of plate-design. Small tubular units have a double-pipe arrangement. The larger ones are designed as shell- and tube apparatus. With plate-heat exchangers we find the basket and the lamella design. With condensation of vapour substances having low latent heat of evaporation extended surfaces with fins on tubes or plates are used.

Examples of evaporators with tubular design are shown in fig.5. This standard

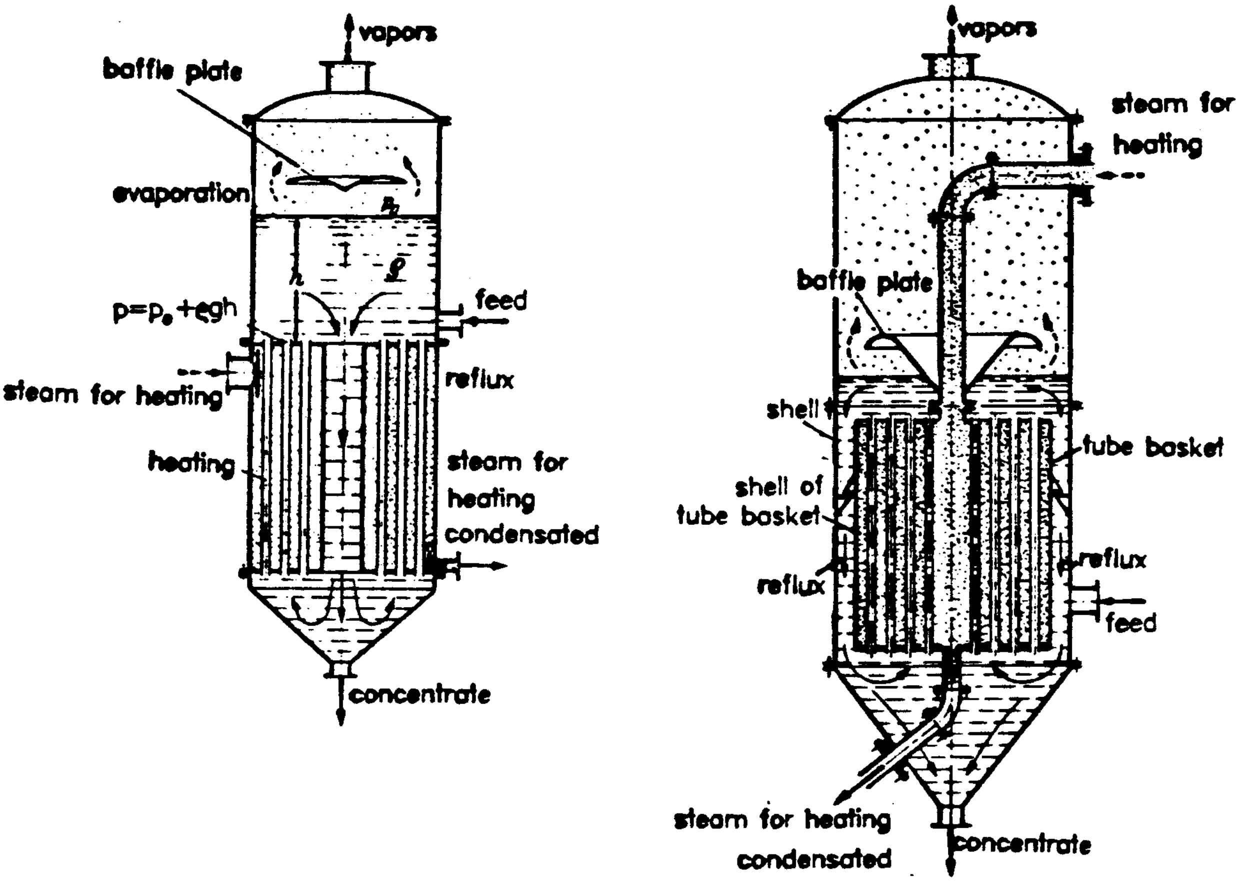

Fig.5: Evaporator with internal and natural circulation, (a., short tube bundle with central reflux, b., basket with annular reflux)

design is frequently used in the chemical industry for concentrating solutions by vaporizing the higher volatile components. The soluble mixture is in a cylindrical vessel which contains a tube bundle in its lower part. These tubes are heated from the outside by condensing steam. The soluble mixture is vaporizing and rising inside the tubes and the recirculation is guaranteed by a bigger central tube - as the left side picture of fig.5 shows - through which the liquid after being separated from the vapour can flow down again. The design on the left side in fig.5 has the disadvantage that this central tube is also heated by the vapour, resulting in a deterioration of the downflow due to lifting forces and too much heat is lost by condensing vapour on the outside vessel wall too.

This disadvantage is avoided in the design on the right side of fig.5. This design is called a basket-type evaporator because the heating arrangement is inserted into the vessel like a basket. The end-plates where the tubes are fixed in are not connected with the wall of the vessel. There is an annular space between the wall of the vessel and the outer shell of the basket through which the liquid can flow down in natural circulation after being separated from the vapour produced during upflow inside the tubes. The cross section for the downflow of the circulation is now much larger, which reduces the pressure drop and enhances the circulation velocity. Another advantage of this design is that the tube-basket can easily be removed out of the vessel for cleaning or repairing.

A next step in designing such a recirculation-evaporator is repairing the channel for recirculating the liquid outside the heat exchanging area of which fig.6 presents two examples. This gives - as shown in the left-hand picture of fig.6 - also the possibility to insert a circulation pump in the downflow channel to increase the circulating mass flow rate. In the example shown on the right side of fig.6 an axial pump is used for circulating the liquid. This allows a high grade of concentration

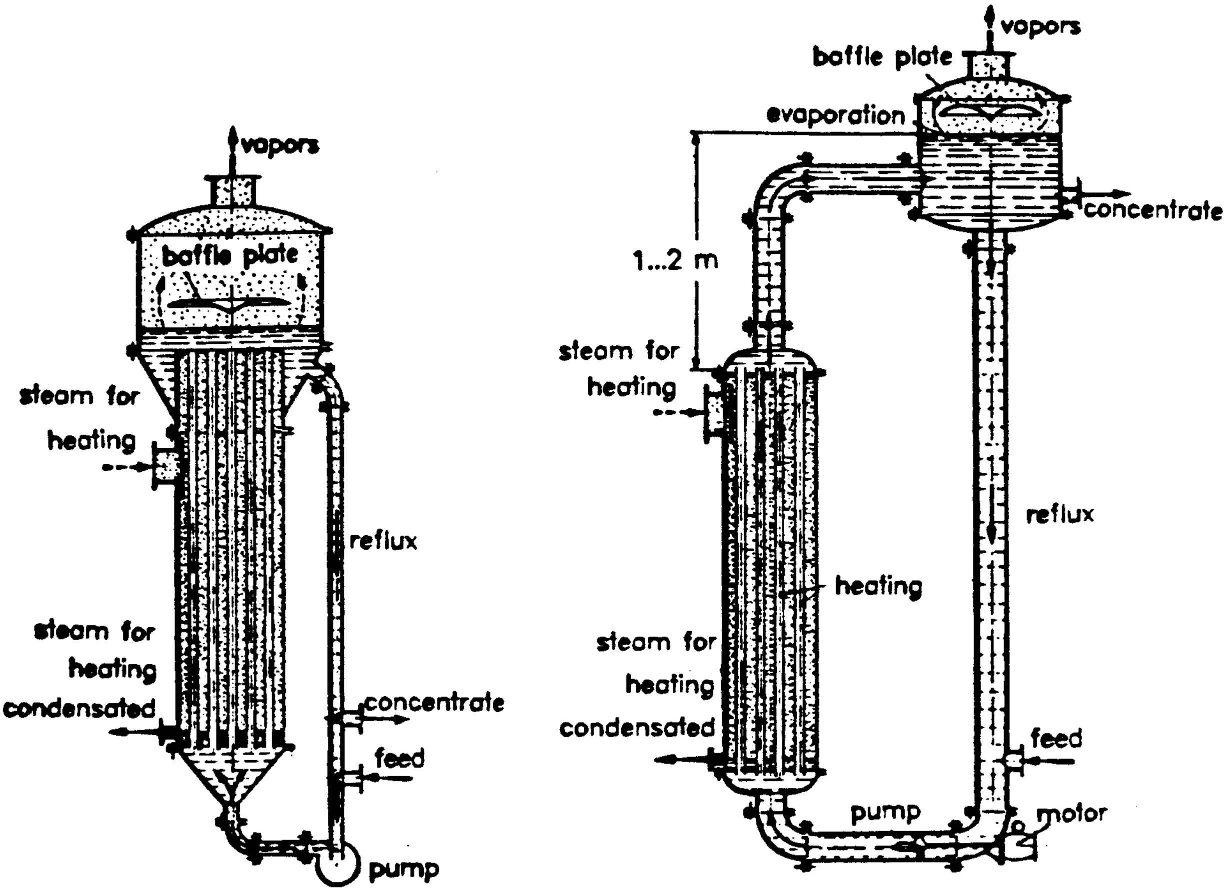

Fig.6: Evaporators with external reflux tube and forced circulation

because also high viscous fluids can be circulated.

Finally we can classify with respect to application. As mentioned above two-phase flow heat exchangers are used in a wide variety of applications as in the process, power, air-conditioning, refrigeration, cryogenics, heat recovery, and manufacturing industries. In fig.7 only a few possible examples are listed. The process-industry is using two-phase flow heat exchangers for vaporizing, condensing - partial condensing, for example as dephlegmator - , freezing in crystallization and as fluidized bed with catalytic reaction. In the power-industry we find various kinds of fossil boilers, nuclear steam generators, steam condensers and cooling towers. The air-conditioning industry needs condensers - also with partial condensation - and evaporators.

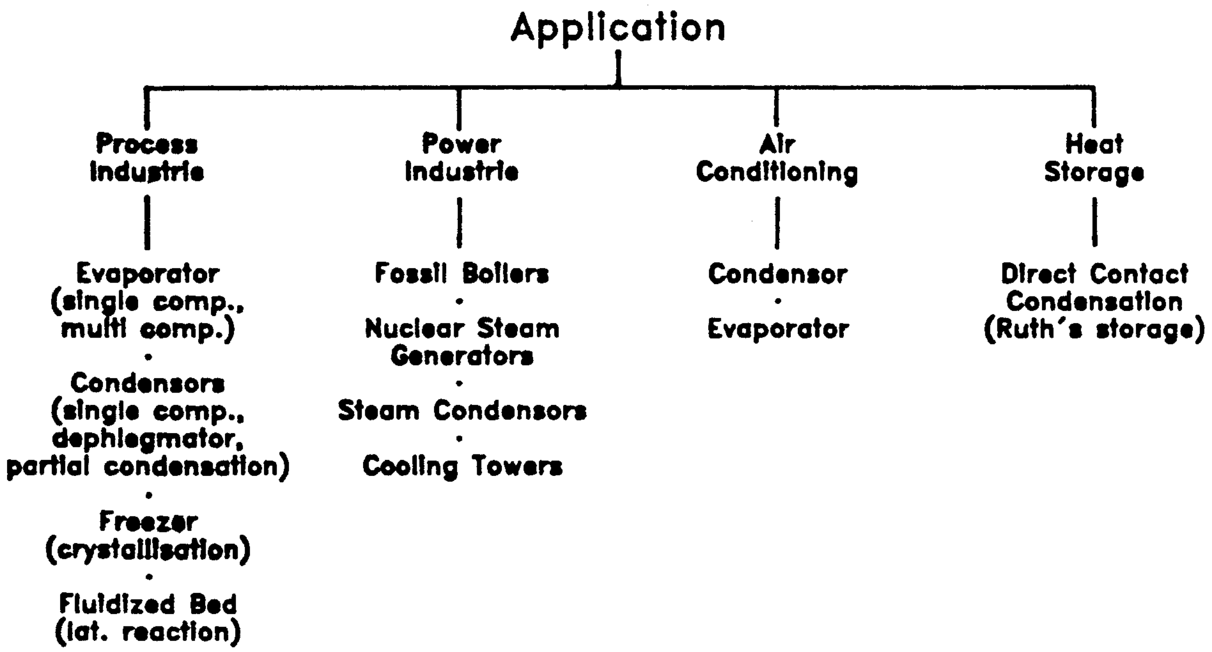

Fig.7: Classification of two-phase flow heat exchangers according to application

With increasing effort for saving energy a regenerative use of two-phase flow heat exchanging becomes more common again, namely the direct contact condensation of vapour in liquid of the same substance in an apparatus which is called Ruth's-storage tank. Heat is stored in the liquid by blowing in vapour under high pressure which is, as mentioned above, condensing. If the heat is needed again the liquid is depressurized by which flashing occurs and the produced vapour can be used for heating or for driving an engine.

3. SPECIAL EXAMPLES OF HEAT EXCHANGERS IN THE POWER- AND PROCESS-INDUSTRY

There was quite a vehement development in heat exchanger design during the last decades especially for power- and process-engineering. In power-engineering there were two reasons for this development, namely the increasing unit per station and the new demands of nuclear plants. Until the end of the fifties fossil fired power-stations had an electrical output of 50 to 100 MWel per unit and modern coal fired power-stations of to-day are in the order of 700-900 MWel.

Nuclear reactors provide energy up to 1300 MWel per unit to-day. This increase in the electrical output means that the thermal power had to grow from 150 to 4000 MWth per station. This was not possible just by scaling the old design furthermore. New kinds and families of boilers and steam generators had to be developed. A similar development was going on with the condensers which had to be increased in their capacity from 100 to 2500 MWth.

In process-engineering economic reasons, higher process temperatures and pressures and last not least also larger units influenced the development of heat exchangers in general and expecially with two-phase flow. Ideas were born, but up to-day not yet executed, to combine a chemical production with a nuclear power-station, to use the nuclear heat from a high temperature reactor for chemical operations.

In the following a few examples will be given demonstrating the development of two-phase flow heat exchangers in power- and in process-engineering.

3.1 Fossil Boilers

To get an idea how fossil boilers changed in their design from the beginning of this century until to-day let us compare an old sectional boiler constructed before world war I with modern ones of to-day working with natural or with forced convection. In fig.8 a design of an old boiler is presented as it was constructed before world war I. Coal was burning on a fire-grate and the hot gas was flowing around inclined tubes which were cooled inside by evaporating water. The water-vapour-mixture reached a horizontal vessel after passing a header being arranged at the upper end of the tube bundle. In the horizontal vessel the water was separated from the steam and the latter one was feeding a steam engine, at this

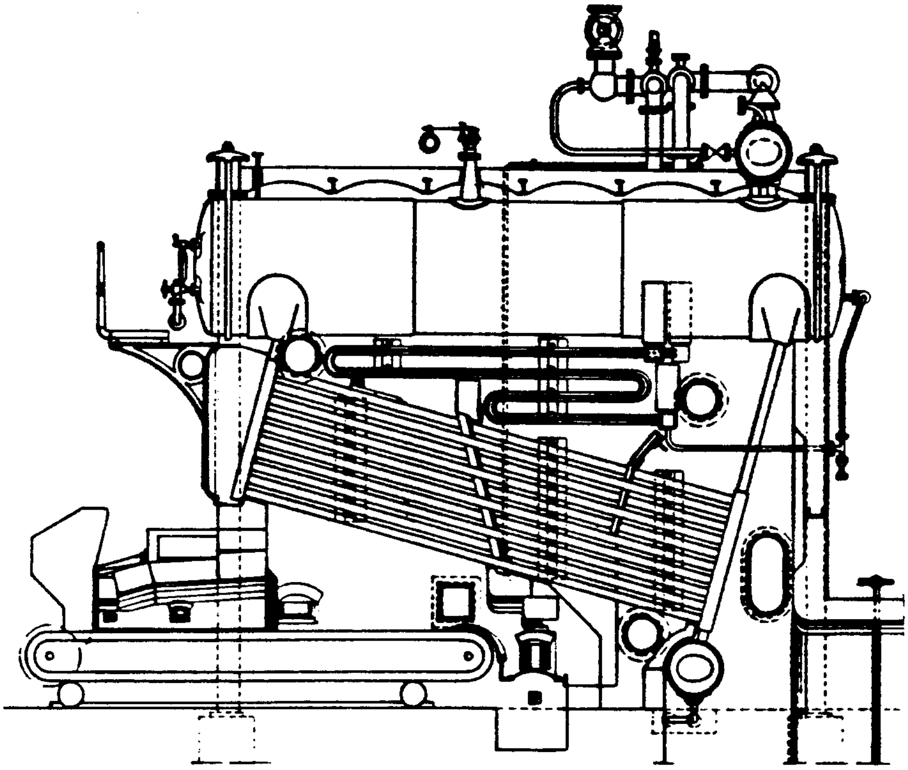

Fig.8: Old Babcock sectional boiler before world war I

time usually of piston design. Only low heat flux densities were applicable at this time, firstly because the coal was burning slowly on the grate and secondly the heat transfer coefficient between the hot gas and the tubes was moderate too. In addition the low velocities of the steam-water mixture in the boiler-tubes did not allow high heat fluxes.

The modern design of fossil fired boilers is completely different to that shown in fig.8. The figs.9, 10 and 11 show examples of modern fossile heated heat exchanger units consisting of zones for water preheating, for boiling, and for steam superheating. The steam generator in fig.9 is working with natural circulation whilst the examples in the figs.10 and 11 are - so-called - once-through steam generators operating under forced convective conditions.

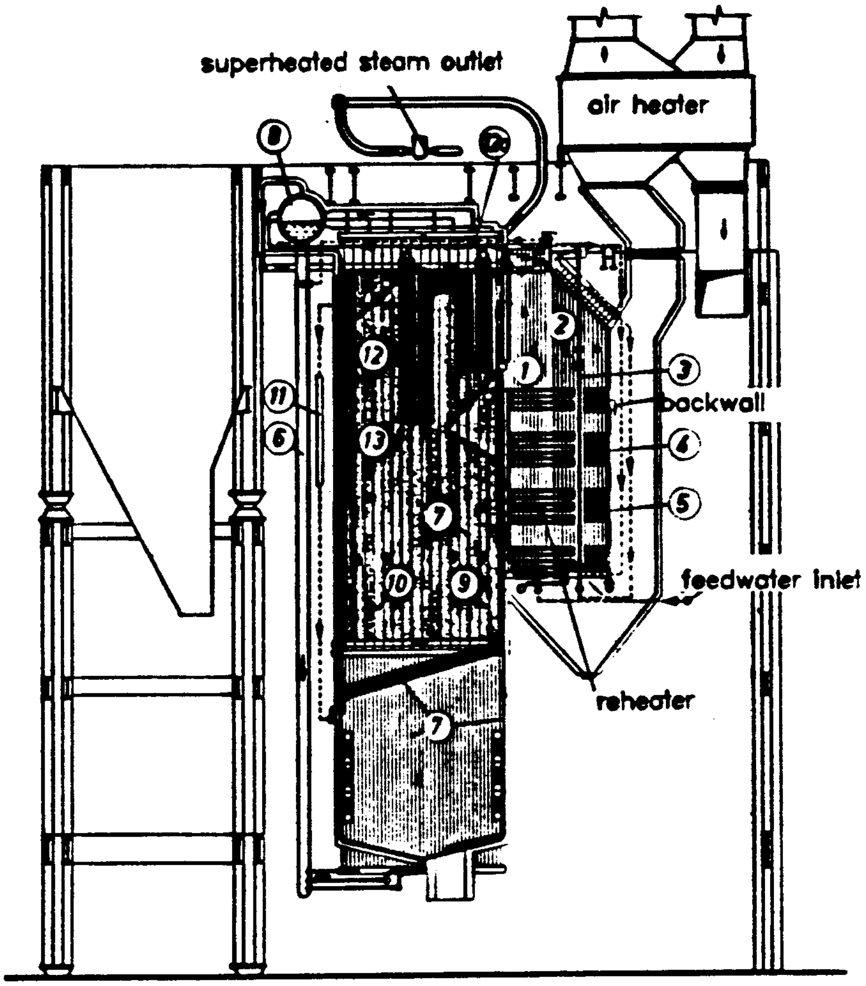

Fig.9: Natural circulation boiler with cyclon-burners (liquid ashes)

fuel	pit coal
steaming capacity	200 t/h
maximum working pressure	175 atü
live steam temperature	535°C

1 - 5 economizer, 6 down-flow tubes, 7 evaporator, 8 vapor drum,
9 - 13 superheater

The boiling zone of the steam generator in fig.9 is heated by radiative and convective heat transfer from the hot gases being the reaction-product of cyclon-burners placed in the lower wall of the boiler. The two superheaters get their energy by convective heat transport from the exhaust gases as well as the economizer for preheating the water before it enters the boiler.

The steam generators in the figs.10 and 11 differ mainly in the combustion process. The steam generator in fig.10 is equiped with a chamber of low heat transfer to the walls where the ashes are collected as melt in a liquid form and transported in this molten condition out of the combustion chamber. The ashes of the steam generator in fig.11 consist of solid small particles.

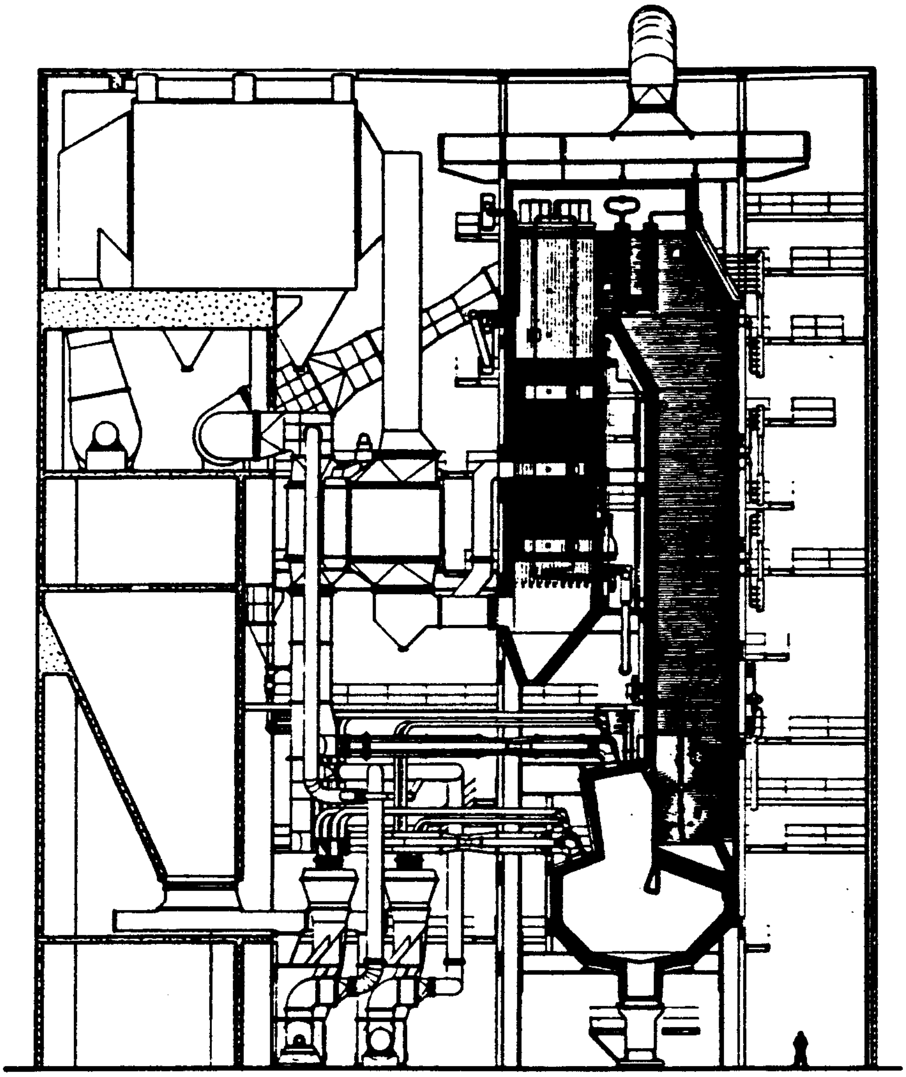

Fig.10: Once-through boiler

fuel	pit coal
steaming capacity	246 t/h
maximum working pressure	210 atü
live steam temperature	530°C

Two-phase flow exists in the boiling zone if the steam generator is operated under subcritical pressure. This is always the case with boilers operating in the natural circulation mode. Once-through boilers mostly have supercritical pressure under normal operating conditions. However, during start-up and shut-down also these boilers are controlled down to 70 bar which means that violent boiling and two-phase flow phenomena occur. Some of these manifold and various phenomena we shall discuss in chapter 4.

The heat transfer elements of steam generators are usually round tubes in which the liquid, the two-phase mixture, or the vapour flows and which have on their outside the heating gas resulting from the combustion process. In the boiling zone there are two different arrangments of these tubes, one with mainly vertical direction and the other one have coiled configuration with a moderate angle of upward inclination.

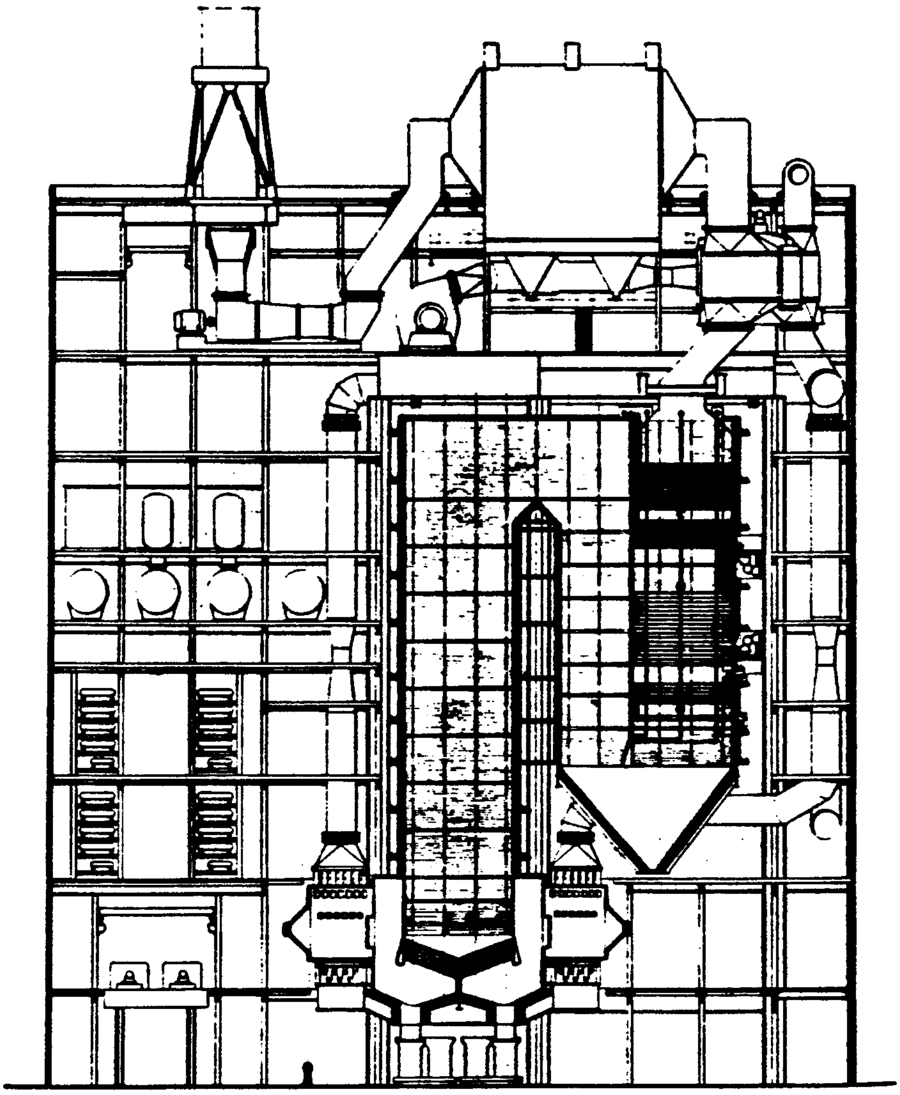

Fig.11: Once-through boiler with cyclon burners

fuel	pit coal and oil
steaming capacity	650 t/h
maximum working pressure	280 atü
live steam temperature	530°C

3.2 Nuclear Steam Generators

Nuclear steam generators are used in water-cooled, liquid-metal-cooled and in gas-cooled nuclear reactors. Their design is depending on the coolant and on its temperature. The only common feature is that all steam generators have tube bundles as heat exchanging elements. However, in steam generators of water-cooled reactors boiling takes place outside of the tubes, whilst with liquid-metal- and gas-cooled reactors the evaporating water flows inside the tubes.

Fig.12 shows a sketch of the principle design of a steam generator for a pressurized-water-reactor (PWR). The primary coolant enters the tube bundle consisting of hairpin tubes via a lower plenum and leaves it through another lower plenum flowing back to the nuclear reactor. The water has a pressure of approximately 160 bar and is cooled down in the hairpins by only 10 K. The tube bundle is surrounded by a cylindrical shell, both - the shell and the tube bundle - being inserted in a pressure vessel. The secondary side water - called feed water - flows down in the annulus between the pressure vessel and the shell and enters the tube bundle from below, above the bundle-support-plate. From there it flows upwards longitudinal to the tubes by free convection evaporating partially on its way.

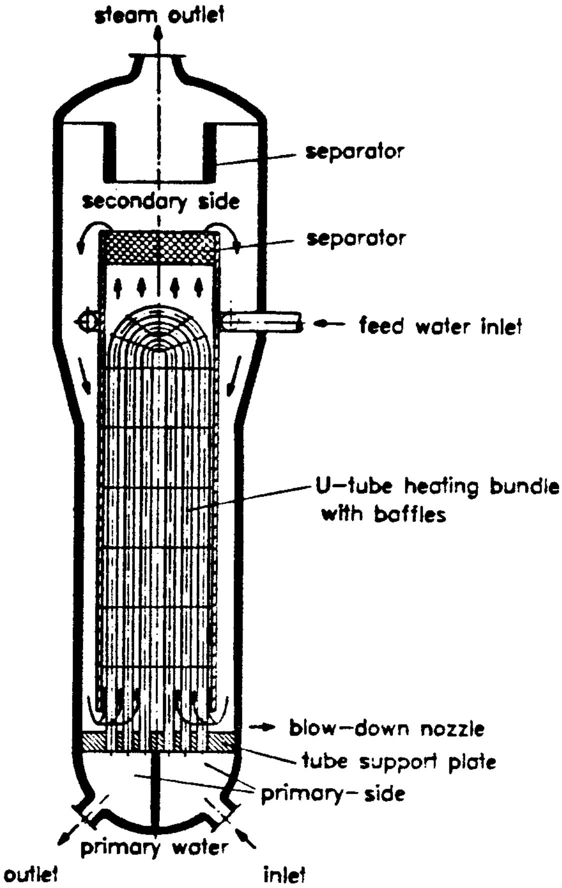

Fig.12: Vertical U-tube steam generator

At the upper end of the cylindrical shell cyclons separate the secondary water from the vapour which ascends in the upper part of the pressure vessel and reaches finally a demistor which separates the entrained water droplets out of the vapour. The upper end of the steam-generator-pressure-vessel has a larger diameter than the lower one. The reason is to facilitate the separation of the water from the vapour by slowing down the rising velocity of the vapour.

The PWR-steam generator operates in natural convection mode with low heat flux densities. Problems were reported due to corrosion at the lower part of the tube bundles just above the support-plate and due to fretting erosion at baffles which may be due to vibration.

The development in size of these heat exchangers from the beginning of nuclear power until to-day shows fig.13. The first PWR's, built end of the fifties and beginning of the sixties, were small experimental- and prototype plants having an electrical output of 50-100 MWe. Modern pressurized water reactors are feeding 4 steam generators each providing steam for 300 MW electrical power. The total power of such a PWR-unit, therefore, is in the order of 1200-1300 MWe. There were intensions some years ago to construct even larger units having a total output of 1600-1800 MWe with 4 steam generators of 400-450 MWe each. However, these ideas are history in the meantime due to the stagnant development in the electrical power consumption. The trend is to-day more oriented to smaller units in the order of 900-1000 MWe.

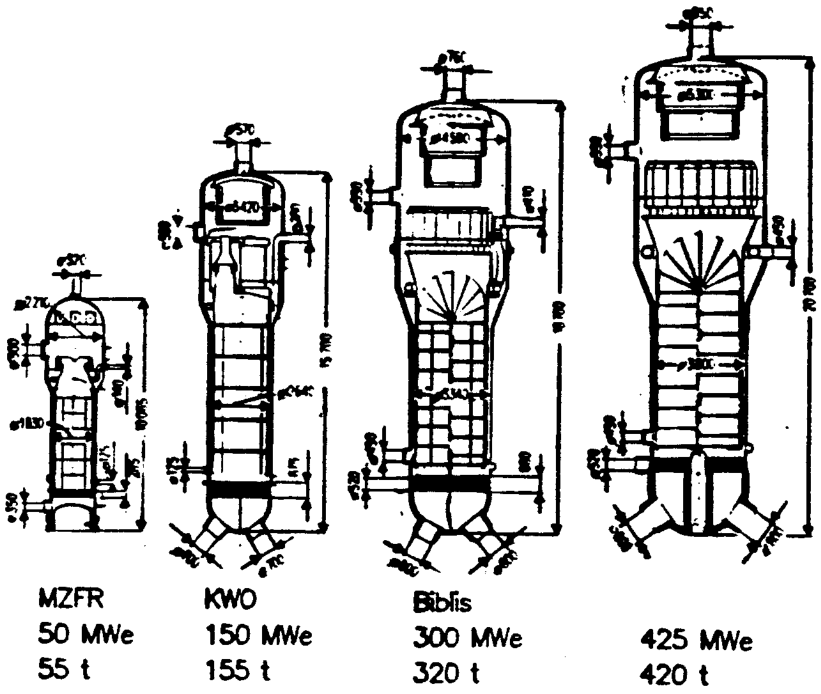

Fig.13: U-tube steam generator with natural convection

The design of steam generators for liquid-metal-cooled nuclear reactors - so-called fast breeders - is completely different from that for PWRs. Fig.14 presents the design of one of the steam generators for the most modern and also largest fast breeder, the French Super Phenix. This steam generator consists of tube bundles coiled in a very complicated manner. To guarantee that each tube has approximately the same length from the inlet to the outlet of the heat exchanging zone the coiling starts from the shell near outside and goes to the center and vize versa.

Water entering the tubes from below flows upward driven by a pump completely evaporating in the heat exchanging area and the vapour produced is finally superheated before it leaves the steam generator at the upper end. The liquid-metal - sodium - enters the shell-side of this heat exchanger from above and is flowing downwards - also forced by a pump until it leaves the vessel at the lower end. So this steam generator works in counter-current-flow.

A steam generator for a sodium-cooled fast breeder must be a product of extremely high manufacturing quality and of sophisticated engineering art. The tube bundle must be completely tight because even the smallest leak would produce

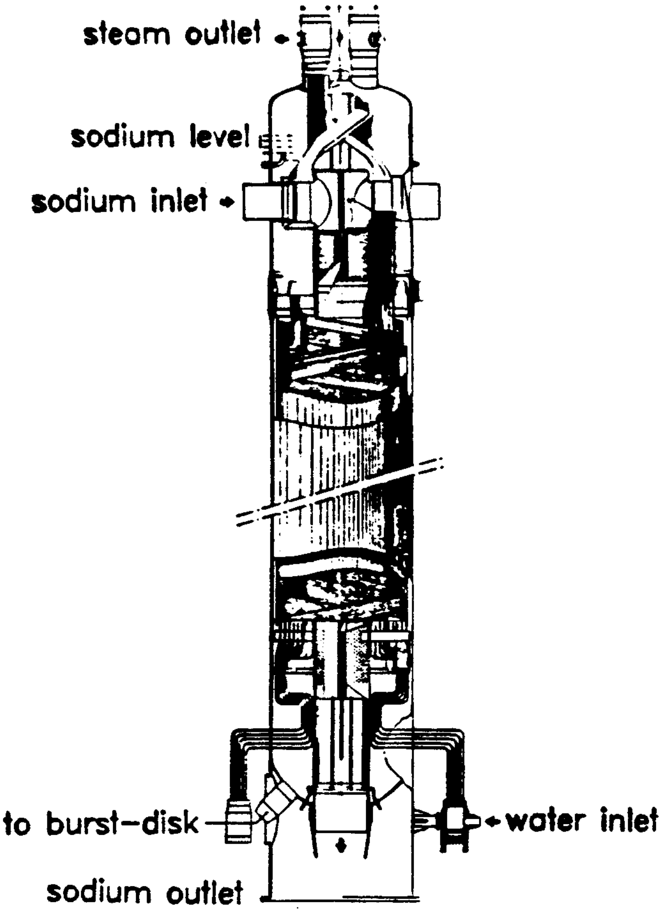

Fig.14: Steam generator for a sodium-cooled reactor

a violent chemical reaction between the water and the sodium. This tightness must be guaranteed through all operating conditions. The once-through mode in which the steam generator works on the water-side brings with it many two-phase flow problems especially with respect to flow stability in these parallel boiling tubes and to a uniform flow distribution on the sodium side.

Steam generators for gas-cooled nuclear reactors look to some respect similar to that of sodium cooled reactors. They also consist of coiled tube bundles. In fig.15 a design is presented how a future gas-cooled reactor unit could look like producing steam for electric power and heat for a chemical process simultaneously. Helium is used as coolant for the fuel elements which is heated up to 950°C. The fuel elements of this High-Temperature Reactor (HTR) consists of graphite balls in which the fuel - uranium or thorium - is mixed in, arranged in a pebble bed. The hot helium flows to the heat exchanger shown on the right side of fig.15.

This heat exchanger consists of two parts. The one part which is heated up at first by the helium and located in the center of the apparatus serves for heating up gas which may be helium again and which provides energy to a chemical process. The second part is arranged in an annular form around this first heat exchanger and is used for producing steam. In both parts the primary helium flows on the shell-side of the tubes. The tube-side contains the secondary helium, as mentioned before, or the water substance which is evaporated and superheated. The tube bundles have a coiled arrangement in both parts. After leaving the steam-generator-part of the heat exchanger the primary helium is flowing back to the nuclear reactor via a compressor.

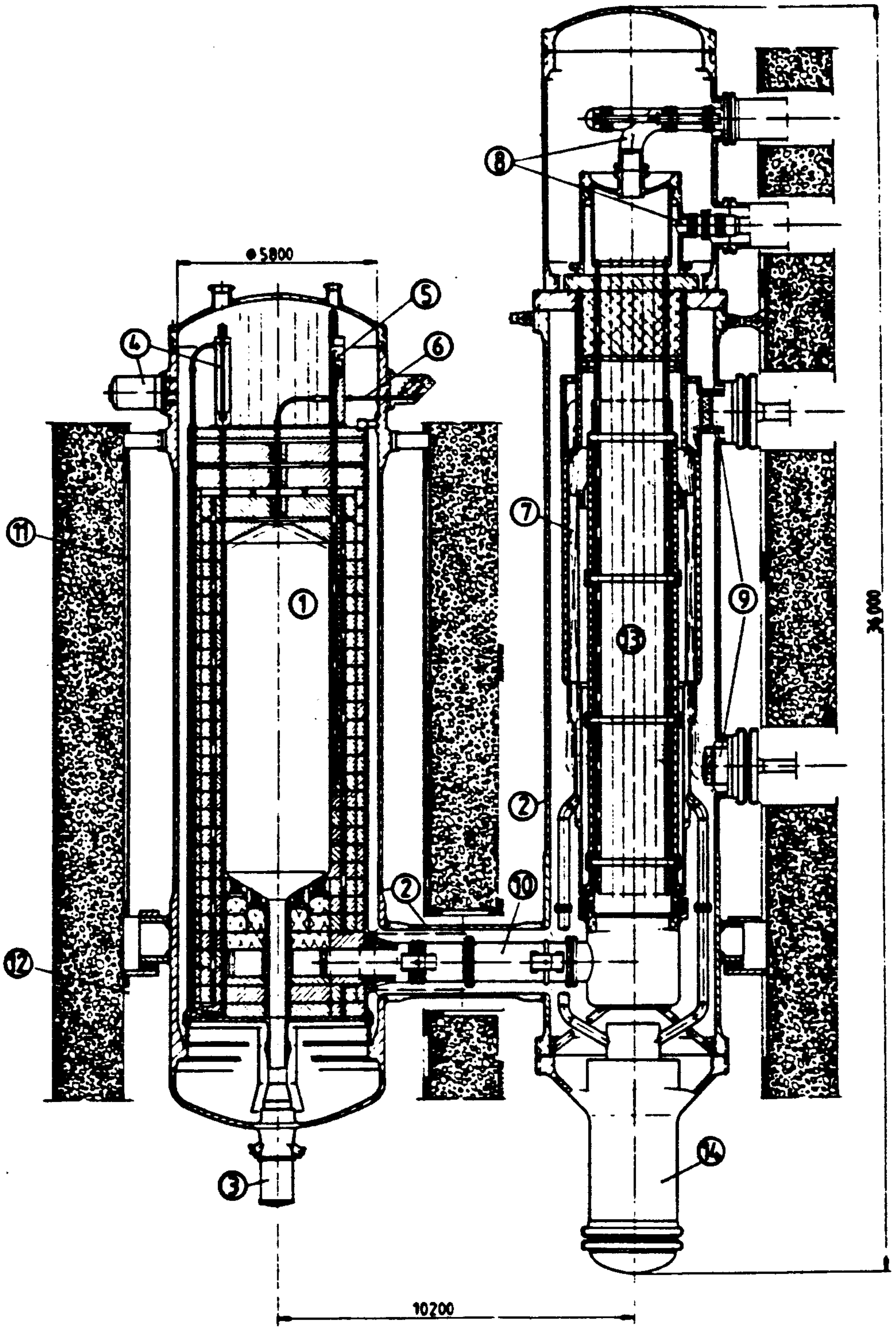

Fig.15: High-temperature reactor modul with tubular chemical cracker and steam generator
1 pebble bed, 2 pressurizer, 3 fuel element outlet, 4 spherical scram element, 5 reflector rod, 6 fuel element inlet, 7 steam generator, 8 connections for crack-gas, 9 connections for steam generator, 10 piping for hot gas, 11 lamella cooler, 12 insulating, 13 tubular chemical cracker, 14 blower

Up to now no unit of such a HTR-nuclear plant is under construction. Before a first unit can start its operation detailed analyses of various safety features of such a HTR-heat exchanger have to be performed. The main handicap of this reactor is the high price per unit of produced energy.

3.3 Process Industry Heat Exchangers

The application of heat exchangers in the process industry shows a wide variety of various design. Temperatures and pressures of heat exchangers in the process industry reach from nearly 0 K up to 2000°C and from vacuum situation up to 4000 bar. These different designs and various applications cannot be discussed here by far. Therefore only two examples are picked out to demonstrate that in the chemical industry a heat exchanger is a complicated apparatus on several occasions or is integrated in a process component.

On the other hand special observations have to be made about thermal stress situations when the heat exchanger is used with high temperatures or with large temperature differences. For example in the industry producing artificial fertilizers ammoniac (NH_3) has to be oxidised. This is an exothermal process and is mostly performed on a catalytic way. This oxidation heat can be used to produce steam which is a feed in the production of NH_3.

Fig.16 shows a design of an apparatus in which a catalytic pepple-bed and heat exchangers for preheating water and evaporating it are integrated. The ammoniac enters this apparatus from above and flows through the catalyst F1 where it oxidises and develops heat. The oxidised and hot ammoniac then flows through the heat exchanger F2 evaporating and superheating steam on the tube-side of the heat exchanger elements. The tubes can be arranged in different way, as shown on the left and right side of fig.16. Flowing downward finally the oxidised

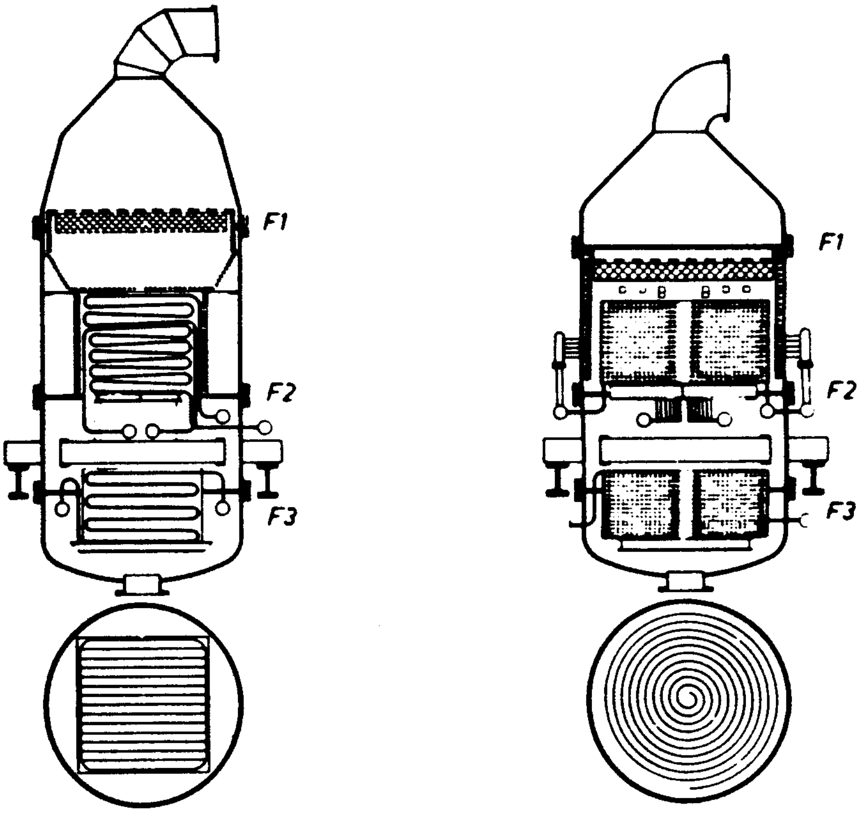

Fig.16: Heat exchanger after NH_3 oxidizing element

where the water is heated up to saturation temperature before it enters the tubes of the heat exchanger F2. So a chemical reactor and heat exchangers are integrated in one apparatus.

The exploitation of the thermal energy of hot exhaust gases having a temperature of 1500-2000° in heat exchangers requires a special design for avoiding unallowable thermal stress. Fig.17 shows details of protecting devices against thermal stress in a high temperature heat exchanger. The hot gas, having high pressure, enters the heat exchanger from below via a well insulated chamber. From there the gas flows into tubes which are the heat exchanging elements and which transfer the heat to boiling water being in free convection condition. In the heat exchanging zone the tubes are coiled. The steam produced outside the tubes by evaporating is demisted in the upper part of the vessel and flows through a nozzle to any user.

The most endangered areas by thermal stress are the penetration positions of the tubes through the wall between the hot chamber, through which the hot gas comes in, and the reservoir of the boiling water. Here temperature differences of more than 1500 K could be present over a distance of a few mm if not a special design would be used. Therefore a insulating and water cooling device is applied. The tubes through which the hot gas enters the heat exchanger are not welded directly into this thick wall as is demonstrated on the right side of fig.17. There is an annular shielding around these tubes in the entrance region. Water is pressed by an injector into a chamber above the wall of the lower plenum and from there it

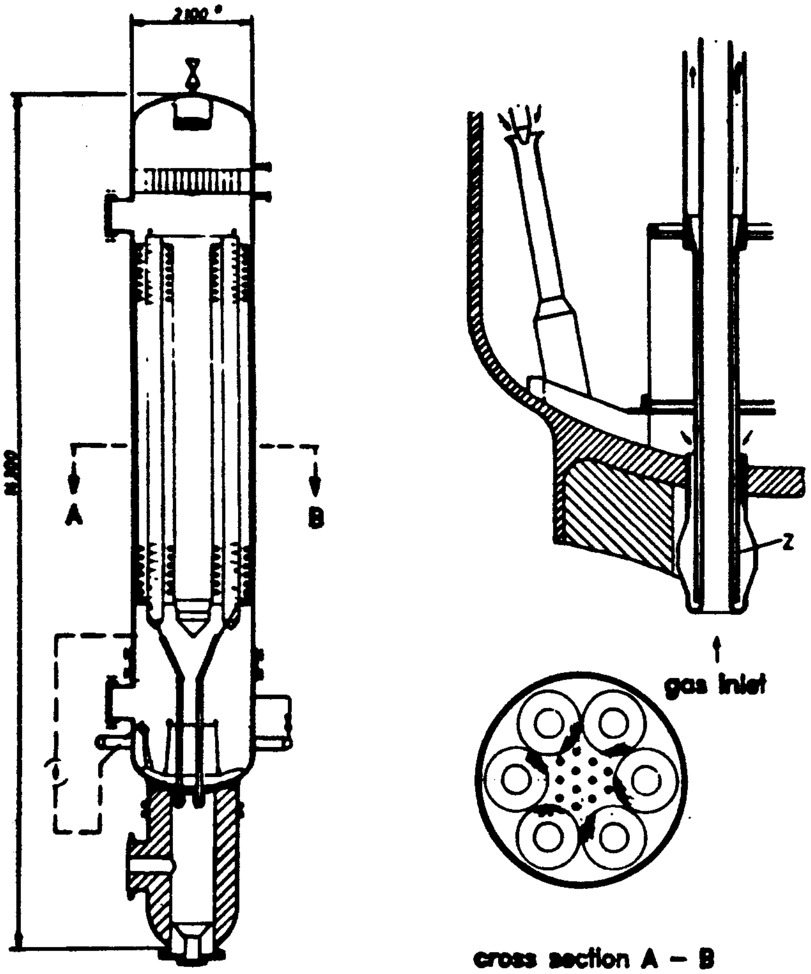

Fig.17: Heat exchanger for high temperature gas

flows downward in the outer annulus of this shielding device. At the lower end of this device it is returned and flows now upwards again in an annular space surrounding the hot gas-tube. Through this annulus of the concentric tubes the water finally flows in the open space of the vessel again. So the high pressure welding connection is cooled and almost no stress can occur in the area where the tubes carrying the hot gas penetrate the bottom wall of the vessel.

The coiled bundles of the heat exchanging tubes can free expand hanging on 6 supporting columns so that also here no thermal stress exists. The outlet of the cooled gas out of the heat exchanger is not shown in fig.17.

So in chemical engineering very often each application needs its special design. Besides temperature and pressure also corrosion due to agressive substances, fouling and sometimes also errosion especially in two-phase flow with solid particles have to be taken in account.

4. PHENOMENA IN TWO-PHASE FLOW HEAT EXCHANGERS

Two-phase flow is of much more complicated nature than single-phase flow. With single-phase flow the knowledge of the velocity distribution is good enough in most cases to describe the flow behaviour sufficiently. In two-phase flow we have to know the density distribution in addition which means that we need information on flow pattern.

Single-phase flow shows a moderate density variation during heating up or cooling down. Two-phase flow carries with it two fluids with densities differing by one or two orders of magnitude each of it having the ability to change its state by boiling or by condensing. So we have much larger acceleration or deceleration in two-phase flow heat exchangers than in single-phase ones. Due to gravity and to pressure forces both phases do not flow with the same velocity which results in momentum exchange between the phases. This momentum exchange is a source of additional pressure loss in the flow.

The heat transfer coefficient is different whether there is liquid or vapour at the wall heated from the other side. In cases of liquid at the wall, the liquid may wet the wall, with bubbles nucleating out of it, or there may be a thin film of slightly superheated liquid where evaporation takes place at the phase interface. Finally, at very hot walls a phenomenon occurs which we call departure from nucleate boiling or burnout having heat transfer coefficients 1 - 3 orders of magnitude lower than with nucleate boiling.

All these phenomena influence the design of a two-phase flow heat exchanger. We will discuss here only a few of them.

4.1 Fluiddynamic Phenomena

Phase separation in the heat exchanging units is influencing the pressure drop as well as the heat transport process. As well known and as illustrated in fig.18 we distinguish between bubble-, slug-, churn-, annular-, and spray-flow. In the first mentioned flow configuration the liquid, in the last one, the vapour is the continuous phase. The transport properties, viscosity and heat conductivity, of the continuous phase are mostly controlling the fluiddynamics and the heat transfer. Phase distribution or flow pattern are a result of interacting forces, as momentum, pressure difference, gravity and surface tension. The literature presents theories - for example by Taitel and Dukler /3/ - which allows to predict the flow pattern for the tube-side flow of heat exchangers, however, for the shell-side flow the situation is much more complicated because in longitudinal flow along the tubes spacers or baffels and in cross flow the tubes itself disturb the flow configuration. Turn around regions in the shell-side flow, in addition, separate the vapour from the liquid so that we cannot further proceed from an, at least, microscopically

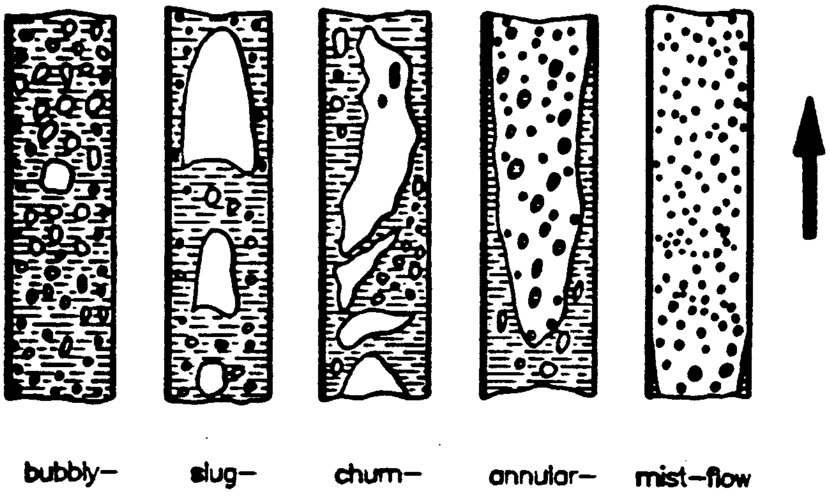

Fig.18: Two-phase flow configurations in vertical tubes

homogeneous two-phase mixture.

As mentioned above both phases are not travelling with the same velocity but the less dense phase is usually by a factor of 1.1 - 2.5 faster than the more dense one. The ratio of the velocity of the vapour to that of the liquid is called slip. This slip influences the local volumetric void fraction because at the same quality x of the vapour liquid mixture, the vapour needs a smaller part of the total cross section of the channel or pipe, than if it would travel with the same velocity as the liquid. The slip is a function of the surface tension, as also mentioned above, and of the density ratio between liquid and vapour. Both properties are a function of the saturation pressure. In fig.19 the local volumetric void fraction is plotted versus the quality and we see that at or near the critical pressure there the slip ratio tends to 1, i.e. quality and local void fraction have the same value. With decreasing pressure the density ratio between the phases is increasing and by this the slip also. From fig.19 we can see the influence of the slip onto the local volumetric void fraction for two different pressures, namely for 1 and 150 bar. The upper curves for these two pressures show the behaviour of the local volumetric void fraction versus quality x if vapour and liquid would have the same velocity - slip = 1 - and the lower one gives the real situation in the two-phase mixture.

By far the largest influence of a second phase can be seen in the pressure-drop behaviour. The second phase is always increasing the pressure-drop due to momentum exchange - resulting in H_2O entropy enlargement - between the phases. There are several correlations in the literature predicting the two-phase flow multiplier which has to be applied to the single phase friction pressure-drop to get the two-phase flow friction pressure-drop. One of this correlations based on several thousand experiments was elaborated by Friedel /5/.

An impression how the second phase can enlarge the friction pressure-drop mediates fig.20. There the two-phase multiplier for friction pressure-drop is plotted versus the quality x for water substance. The two-phase multiplier R in fig.18 is defined as the quotient of the pressure-drop of the two-phase mixture to that of single phase water flow, if in both cases the same mass flow rate exists. One can see that with low pressures the transport of the same mass causes by a factor of several hundred more friction pressure-drop than pure liquid flow. Due to the smaller density ratio between liquid and vapour this two-phase multiplier is reduced with increasing pressure.

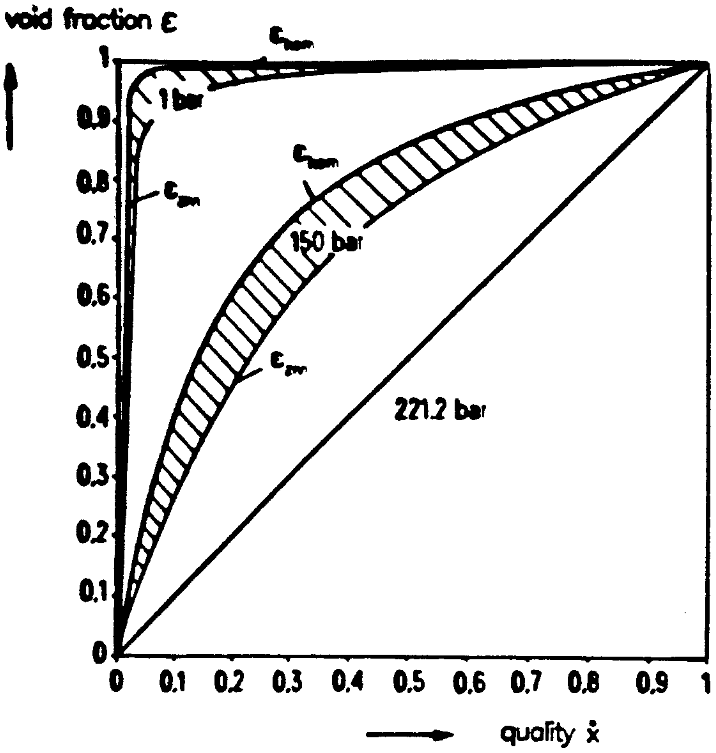

Fig.19: Void fraction as a function of quality

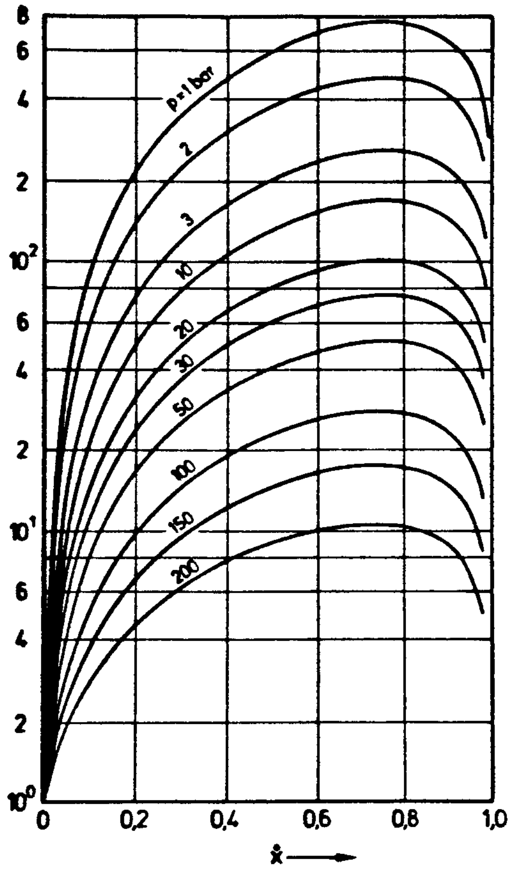

Fig.20: Pressure drop of a mixture of steam and liquid water as a function of quality (multiplier for two-phase flow with respect to liquid water flow)

4.2 Heat Transfer Phenomena

As mentioned above the heat transfer between the wall and the two-phase mixture is depending on the flow situation in the immediate vicinity at the wall. With liquid as continuous phase and low vapour content there is nucleate boiling at the wall and this nucleation process prevails the shear stress situation and the velocity distribution. Therefore, the heat tranfer coefficient with nucleate boiling is almost independent from the velocity of the liquid. However, when the vapour content increases the flow pattern of bubbly flow may change to churn and to annular flow. With annular flow we have to be aware that a noticeable part of the liquid is not transported as liquid film at the wall but as entrained droplets in the vapour flow. This means that the thickness of the liquid film at the wall is in reality much less than one would calculate assuming no entrainment. Already at the beginning of annular flow, i.e. when churn flow changes into the annular form, much liquid flows with the vapour in the middle part of the channel or tube. Fig.21 gives an impression of the distribution of the phases in annular situation.

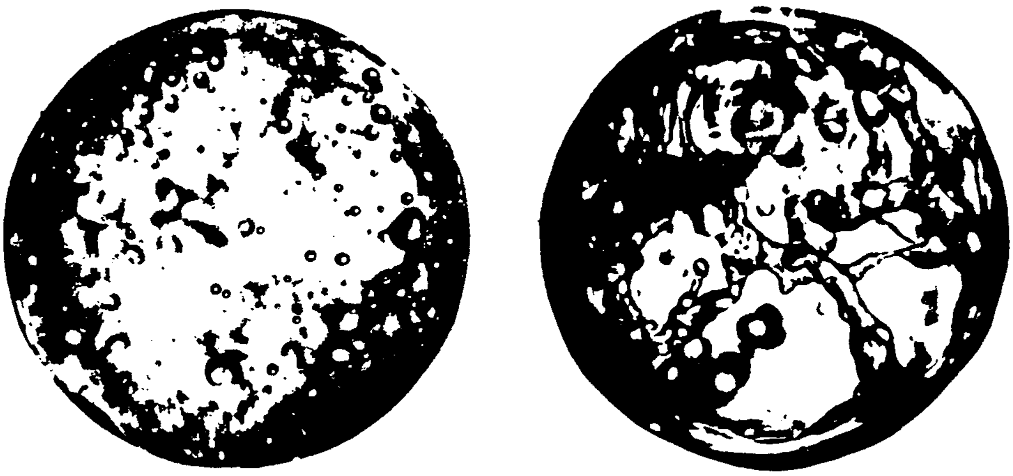

Fig.21: Entrainment and distribution of a liquid film at the wall in a tube

A fluid flowing in a channel to which heat is added from the walls always has a temperature gradient in the boundary layer near the wall. In the vicinity of saturation conditions with high heat fluxes the liquid boundary layer may be superheated, i.e. its temperature is above the saturation temperature, whilst the bulk of the fluid is subcooled. This leads to a phenomenon which we call subcooled boiling.

With subcooled boiling bubbles nucleate in the superheated boundary and start to condense again as soon as they leave the superheated region and come in contact with the subcooled bulk. The onset of subcooled boiling under high heat fluxes may be at bulk temperatures which are up to 100 K below saturation temperature. Fig.22 gives an impression how the onset of subcooled boiling is depending on the flow velocity or on the mass flow rate. In a tube bundle where boiling occurs on the shell-side the subcooled boiling border shows a sinusoidal course around the tube. As shown in fig.22 subcooled boiling starts earlier in the narrow gap between the tubes and this boiling border moves upwards in the diagonal space. On the right side of fig.22 the onset of subcooled boiling for these two positions at the circumference of the rod is plotted for a pressure of 100 bar in water substance. All conditions below the curves in fig.22 represent situations without subcooled boiling and above these curves subcooled boiling starts. For the isotherm of 60 K

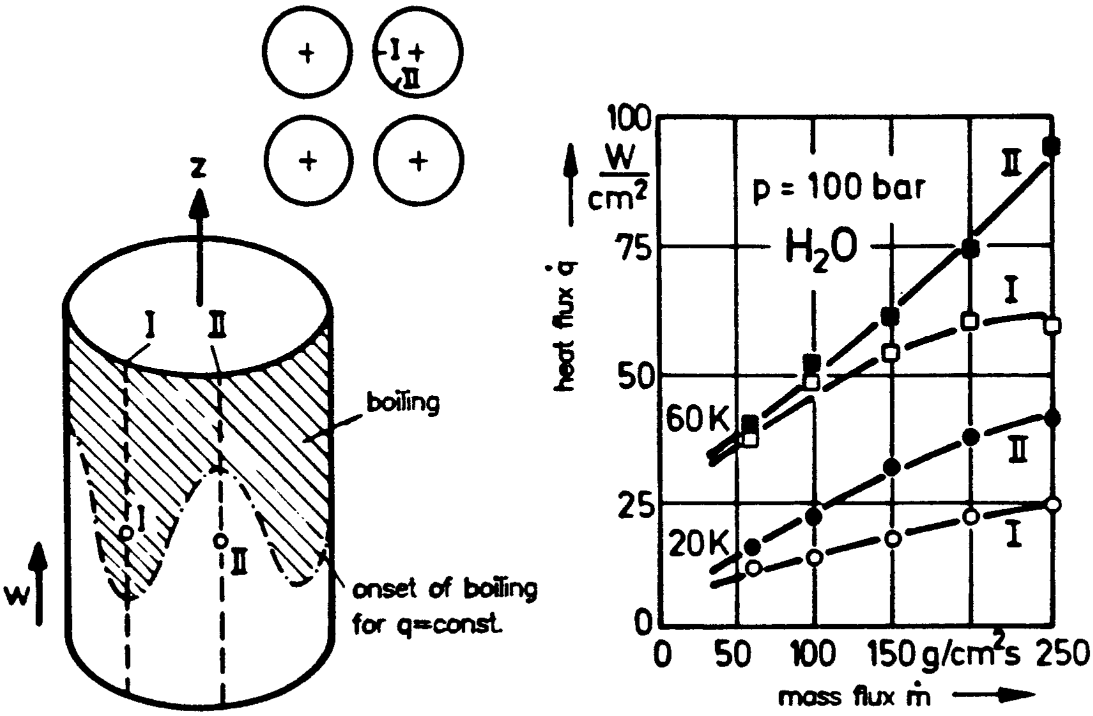

Fig.22: Onset of subcooled boiling in water under forced flow conditions

below saturation temperature with moderate mass flow rates subcooled boiling can be observed already with heat flux densities below $50\ W/cm^2$.

With fully developed boiling and high heat fluxes we observe another phenomenon. Increasing the heat flux with constant inlet conditions to the tube or channel we at first observe an enhancement in the heat transfer coefficient. Exceeding a certain limit - the so-called critical heat flux - the wall suddenly becomes very hot which is due to a change in the heat transport process. Looking to the wall we now realize that the liquid is not any more wetting the wall but a vapour cushion was formed between the wall and the liquid insulating due to low transport properties. This situation is called film boiling. Qualitatively the course of the heat transfer coefficient and the temperature of the wall with increasing heat flux are shown in fig.23, for water substance under low pressure. With higher pressures and high flow velocities the critical heat flux can reach values up to 500 W/m^2 and more.

This critical heat flux with departure from nucleate boiling very rarely occurs in fossil fired boilers. However, the fuel elements of water cooled reactors can come in the vicinity of this situation because they have much higher heat fluxes than the vaporizer tubes of fossil fired boilers. The design of nuclear fuel elements must be safe against critical heat flux.

In fossil fired boilers operating under subcritical conditions, however, also a sudden temperature rise may be observed at a certain position of the tubes. This situation always occurs in once through boilers at the end of the evaporating zone. If we could have a detailed look to the flow pattern at this condition we would realize that the thin liquid film existing at the wall is interrupted by dry patches, i.e. the liquid film is locally drying out. Therefore this phenomenon is called dryout. At the beginning the dry patches can be rewetted again for short periods. A short distance downstream finally the wall becomes completely dry and the temperature is increasing within this short distance by several hundred K. The measured course of the wall temperature in a boiling tube around this dryout region is shown in fig.24. The measured values there are marked with small circles. For comparison also predicted data calculated with various correlations are plotted in fig.24. One can realize that quite a discrepancy exists in the literature. This discrepancy results from the assumptions made about the heat transport process near the wall.

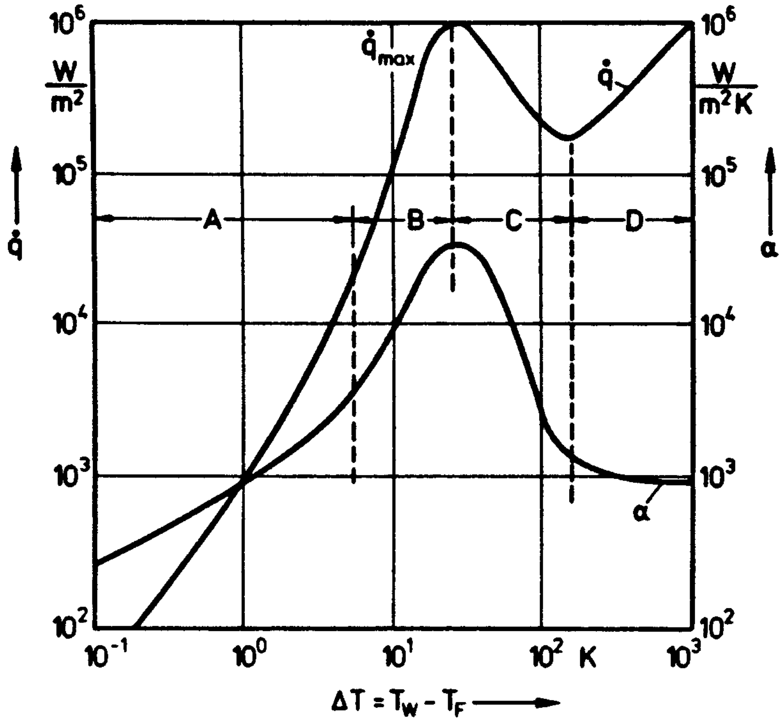

Fig.23: Wall temperature and heat transfer coefficent as a function of heat flux with nucleate and film boiling in water of low pressure

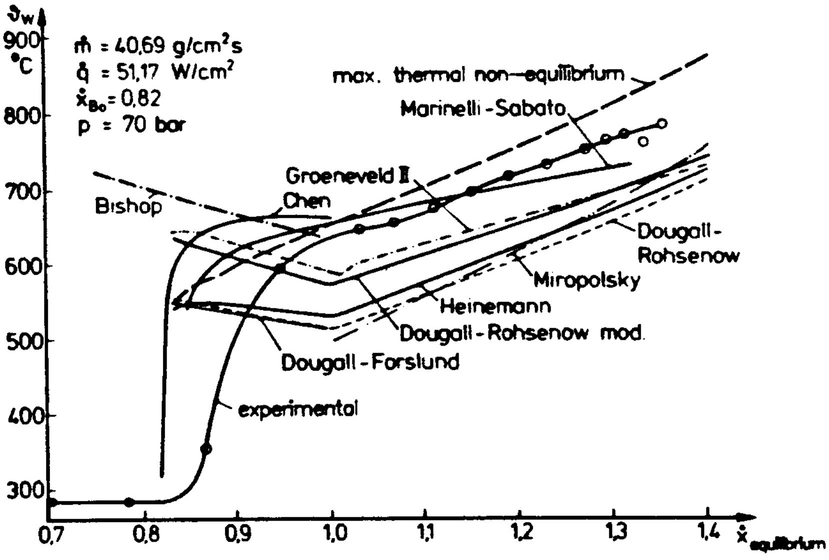

Fig.24: Temperature course in a boiler tube near dryout

In the post dryout region the liquid cannot wet the wall and superheated vapour exists in the boundary layer near the wall. However, droplets are entrained in the vapour flowing in the bulk. These droplets migrate by turbulence or by centrifugal forces outward to the wall. Entering the boundary layer near the wall these droplets can experience various heat transfer phenomena via the superheated vapour or directly from the wall as demonstrated in fig.25. Small droplets or droplets with low radial velocity do not touch the wall because the vapour production on their hot side, facing the hot wall, generates a momentum reflecting the droplet from the wall. If the kinetic energy of the droplet is high enough the droplet can contact the wall, however, it does not wet it. Film boiling occurs under the droplet at the wall and by the violent vapour production the droplet is disrupted and several smaller droplets are formed. This phenomenon improves the heat transfer because the phase interphase is enlarged by this droplet disruption.

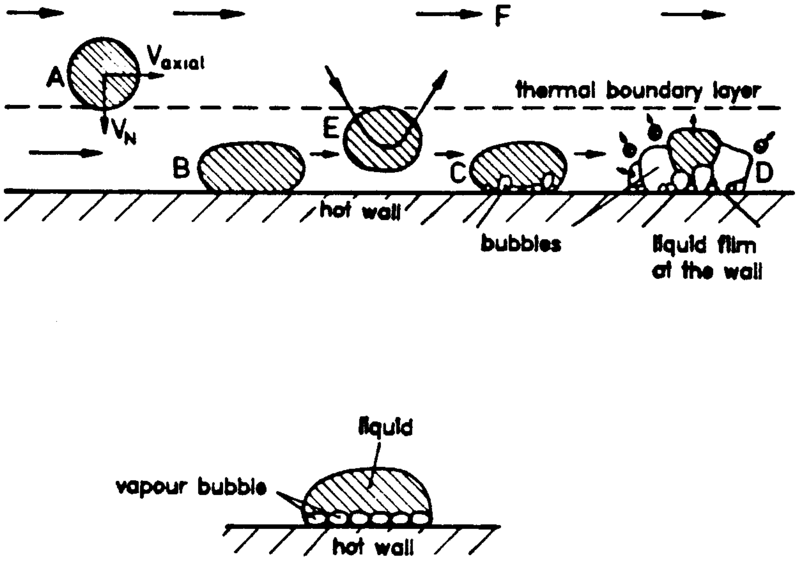

Fig.25: Interactions between wall and droplets under post dryout conditions

Finally fluiddynamic phenomena and heat transfer phenomena can interact witheach other. This, for example, can result in flow instabilities with a sudden break down of the flow or with periodic flow fluctuations. In the literature several different kinds of instabilities are reported like density instabilities, pressure instabilities, or flow pattern instabilities depending which physical phenomenon is causing the instability, namely a density variation, a misbalance between pressure drop and pump head, or a sudden change in the flow pattern. Instabilities are more likely under subcooled conditions than in the high quality region.

This short chapter cannot and will not claim to discuss all thermohydraulic phenomena being of interest in two-phase flow heat exchangers. Only a few examples should be given here. A detailed treatment of relevant phenomena in two-phase flow heat exchangers would demand a discussion of almost the whole two-phase flow theory which is not possible here.

5. CONCLUDING REMARKS

The explanations of this paper only intend to give a brief introduction to the following papers dealing with the design and operation of various kinds of two-phase flow heat exchangers in detail. Aim of this presentation was to illuminate the great variety of two-phase flow heat exchanger concepts and the interesting thermo- and fluiddynamic phenomena being of importance in their design.

Up to the fifties of this century the design of a boiler for example seemed to be more a handicraft or an art than a science. Increasing research in two-phase flow especially during the last three decades generated the scientific basis for a more sophisticated design of two-phase flow heat exchangers and enabled a more efficient and safer operation. However, still much more research is needed to come to an optimal design of two-phase flow heat exchangers in any respect. In addition new applications of these apparatus demand additional experimental and theoretical effort.

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