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Design and construction experiences of multi-stage flash evaporator module train for 4500 m^3/day MSF plant coupled to nuclear power plant at Kalpakkam

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ABSTRACT

The flash evaporator modules are the core installations of any MSF Desalination plant. These are normally rectangular modules consisting of brine flash chambers and vapour condensers generally mounted at high elevations based on NPSH considerations of brine re-circulation pumps. BARC has recently constructed a 4500 m^3/day MSF Desalination plant coupled to 235 MWe nuclear reactor at Kalpakkam in the southern region of India. The plant consists of 39 nos of flash evaporation stages distributed among 10 nos of large flash evaporator modules of different sizes, arranged in a longitudinal layout (long tube design). The smallest of these modules has internal dimensions 2.20 m width, 2.95 m height and 11.30 m length and the largest module is 3.10 m wide, 3.50 m high and 16.30 m long. Major materials of construction include carbon steel, stainless steel, cupro-nickel and inconel. The rectangular geometry, massive size, number of internal compartments, built in condenser, the corrosive seawater environment, etc. make the design and construction of these modules different from conventional process equipments. In this paper, mechanical design and construction experiences of these modules are described covering design and construction features of the modules, construction methodologies adopted, its qualifications, problems faced during construction, etc.

1. Introduction

A widely used method of extracting fresh water from seawater on a large scale is by distillation in a multistage flash evaporator. The principle of the process simply stated is that the amount of energy, which can be stored in water at its boiling point, decreases as the water pressure, which fixes the boiling temperature, is reduced. Therefore, when hot brine at its boiling point flows in to a vessel at a lower pressure, the energy in excess of that which can be contained by the liquid produces vapours. This loss of energy causes the brine temperature to fall to its saturation temperature at this lower pressure. If the brine is then passed in to a second vessel maintained at a still lower pressure, the same phenomenon occurs and more vapour is generated. This technique of vapour production is called flashing. The Multi-Stage Flash process is characterized by the fact that all the energy required is added to the brine before flashing is permitted to begin, and during the process of vapour release over multiple stages, no additional energy is added. The water vapour generated in each stage is condensed on the tube bundle carrying colder incoming (re-cycle) brine to the brine heater. (The brine heater is shell and tube heat exchanger, in which temperature of the pre-heated brine is raised to the desired level using steam from a nuclear power plant). Thus major part of heat expended in evaporation in the stage is recovered in heating the incoming brine. The performance of an MSF plant is dependent on the efficiency of heat recovery, which can be increased by increasing the number of stages. The number of stages is however limited by the increase in hardware cost.

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BARC has recently constructed a desalination plant of 4500 m^3/day capacity, using Multi-Stage Flash Distillation process at Kalpakkam as part of their Nuclear Desalination Demonstration Project (NDDP). The mechanical design and construction features of the multistage flash evaporation modules being used for this plant are described in this paper.

2. Process requirements of the evaporator modules in brief

For the MSF plant at Kalpakkam, the number of stages is fixed at 39 based on the economics of heat recovery and cost of construction of additional stages. These 39 stages are spread across nine heat recovery modules having four stages each and one heat rejection module having three stages. For proper flashing performance, a uniform minimum level of brine has to be maintained in the flash chambers. Uneven levels of brine may be salt deposition and scaling on the flash chamber walls due to non-uniform flashing rates. Hence, a geometry with the flat bottom surface is preferred for the flash chambers. Hence, a rectangular geometry was chosen for the flash modules of the MSF plant. The width of each stage is decided based on the amount of brine feed and allowable brine flow rate per unit length of the chamber width, for choked flow conditions of the two-phase fluid–vapour mixture. The length of each stage is such that the brine leaving the stage and the vapour produced in the stage achieve thermal equilibrium (equilibration). The vapour produced in each chamber passes through a mist eliminator to remove brine entrainment from the vapour. In order to limit the size of the entrained brine droplets reaching the demister, the same has to be kept above certain minimum height from the brine level. Space above the demister level shall be adequate to direct the vapours to the condenser tube bundle with desired velocity. The height of the stage is decided based on these factors. As the temperature and pressure are gradually reduced across the stages, the width, length and height of the stage increase. For the 4500 m^3/day MSF plant at Kalpakkam, the nominal stage width increases from 2.20 m in the first stage to 3.10 m in the last stage, the stage length increases from 2.75 m to 4.40 m and height increases from 2.80 m to 3.75 m. The smallest module consisting of the first four stages is having nominal internal dimensions of 2.2 m width × 2.80 m height × 11.30 m length. The largest module consisting of stages 33–36 is having nominal internal dimensions of 3.10 m width × 3.75 m height × 15.63 m length. Thus even for an MSF plant of this capacity, the sizes of the flash evaporator modules are very huge, resembling a railway wagon and the full assembly like a train as shown in Fig. 1.

Fig. 1. A view of the MSF module train after thermal insulation.

These modules operate under pressures ranging from 2.0 kg/cm^2 (absolute) to 0.08 kg/cm^2 (absolute) and temperatures ranging from 121ºC to 40ºC. The differential pressure across the stages varies from 0.15 kg/cm^2 (1500 mm water column) across stages 1 and 2 to 0.015 kg/cm^2 (150 mm water column) across stages 38 and 39. The process further demands that these modules be mounted at an elevation to provide adequate NPSH to the brine re-circulation pumps. It is also essential that the vapours produced in one stage do not leak into the adjacent stage, bypassing the demister and condenser tube banks. The layout adopted for the plant is to suit long tube design wherein the modules are mounted linearly like a train, from the considerations of pressure losses and the reduced number of tubesheets.

3. Mechanical design of the module

3.1. Design for pressure

Rectangular geometry is not commonly used for pressure vessels, unless demanded by the process. In the case of cylindrically shaped vessels, pressure induces membrane stresses in the vessel walls and geometry gets more or less uniformly dilated. However in the case of rectangular vessels, even low and moderate pressures induce heavy bending stresses on the walls, which tend to bulge out the sides and buckle the edges inward. Membrane stresses also get induced in the rectangular vessels. The design of MSF modules is thus based on both membrane and bending stresses for both internal and external pressure cases. The design is carried out as per ASME Boiler and Pressure Vessel Code Section VIII

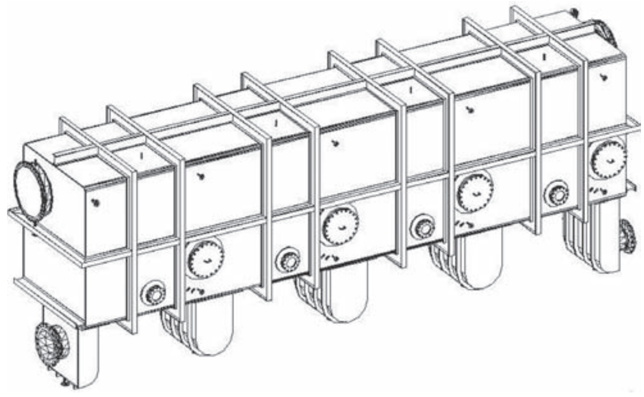

Fig. 2. A typical module construction.

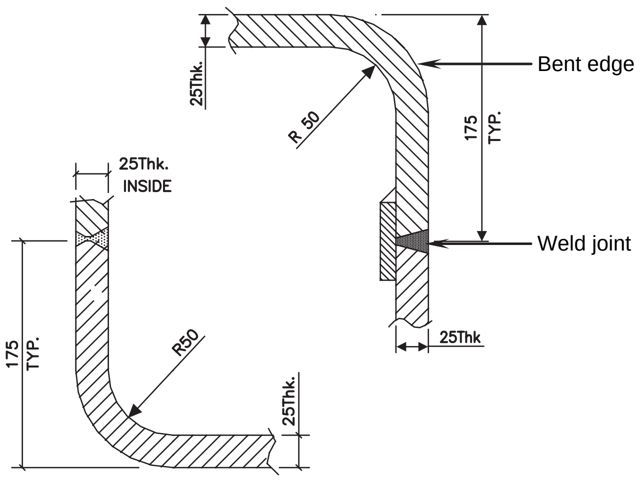

Fig. 3. Joints are shifted from the corners of the shell.

Division 1, which has a separate Appendix devoted for vessels of non-circular cross section.

Due to the presence of huge bending stresses even at moderate design pressures, the rectangular vessel designs need heavy stiffeners on the vessel walls (Fig. 2). The shell thickness can be optimized by varying the amount of stiffening to suit the design condition. We have used the same shell thickness for all modules of our plant and varied the size and numbers of stiffeners. Unlike in the case of cylindrical vessels, the membrane stresses may not be uniform across the section of a rectangular vessel. The shorter sides will have higher membrane stress compared to longer sides. The bending stresses vary along the length of each side, maximum values being at the middle and at corner locations. At each cross section, the membrane stress is added algebraically to the bending stress at both the outermost and the innermost surfaces. Because of the variation in the stress distributions, it is possible to construct rectangular modules with different thicknesses for different sides and even same side having varying thicknesses, though with associated fabrication bottlenecks. Such optimization may however make better economic sense for very large plants. For the modules for our MSF plant, the design thickness of the shell has been kept constant at 15 mm excluding corrosion allowance, by designing the stiffeners suitable for the design parameters of different modules.

Actual shell thickness provided in for the module shell is 25 mm considering corrosion allowance of 10 mm. Joints along the edges in the rectangular vessels increase the design thickness substantially as such joints can be accorded only the lowest possible efficiency values. Making high integrity joints along the edges is relatively difficult and it is equally difficult to have them meaningfully inspected. However by shifting them to relatively less stressed regions, high efficiency butt joints could be made with relative ease and this can reduce the design thickness drastically. This is achieved by forming the shell plates, which permitted shifting weld joints away from the edge as shown in Fig. 3.

3.2. Design for temperature

The maximum operating temperature of the flash evaporator module is at which brine enters the first stage of the module train (121ºC) and the minimum is when it leaves the last stage (40ºC). The mechanical design of the modules has to address the following major consequences of temperature on the module namely (a) the differential thermal expansion of the tube bundle with respect to the shell (b) thermal isolation of the module from the civil foundation, while permitting free expansion of the module and (c) isolating the individual modules from the thermal expansion of the adjacent modules in the long layout.

3.2.1. Design of tube bundle

The tube bundle running full length of each module is positioned above the product compartment (refer to Fig. 4 showing the sectional view of a typical module). The vapour produced in the flash chambers gets condensed over the tube bundle to produce the product water. The tube bundle consists of 1200–1500 nos of tubes of 19 mm OD. The tubes are arranged in a circular layout on the triangular pitch of 24–34 mm. The tubes and tubesheets are made of cupronickel 90:10 materials. The mechanical design of the tube bundle is carried out as per TEMA code. Tube bundle designs with fixed tube sheets and floating tubesheets were verified for

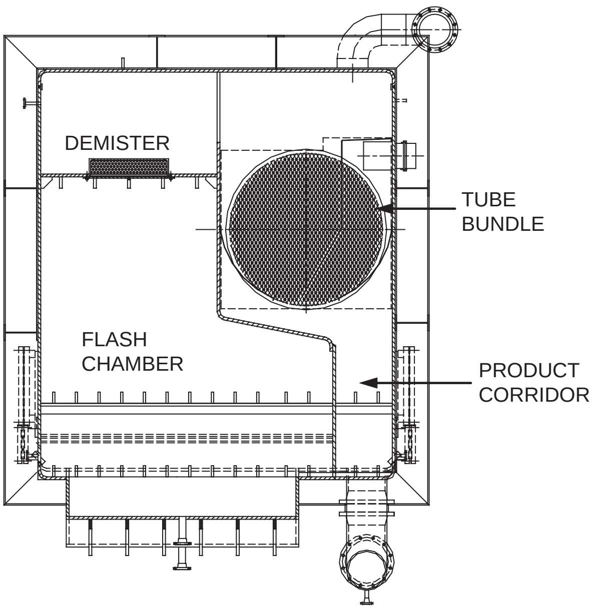

Fig. 4. Typical sectional view of MSF module.

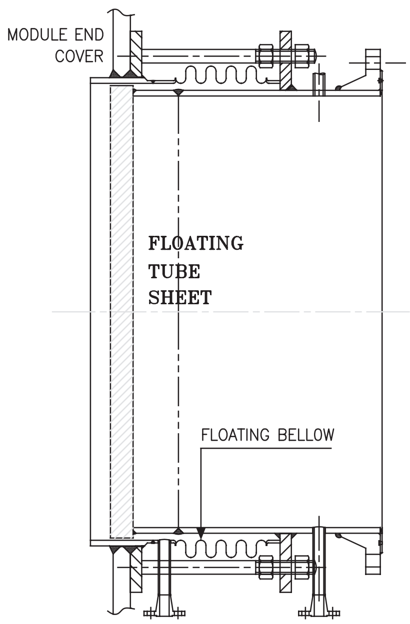

Fig. 5. Floating tubesheet joint.

normal operation as well as possible abnormal operating conditions. The maximum differential expansions of tubes over shell are between 4.5 mm and 14 mm. Fixed tubesheet designs were not feasible for most of the modules. Thus modules 1–8, operating higher temperatures, are designed with floating tubesheets and modules operating at relatively lower temperatures are designed with fixed tubesheets. The floating tubesheet joints are bellow sealed as shown in Fig. 5. The bellows are designed for an axial movement of up to 25 mm.

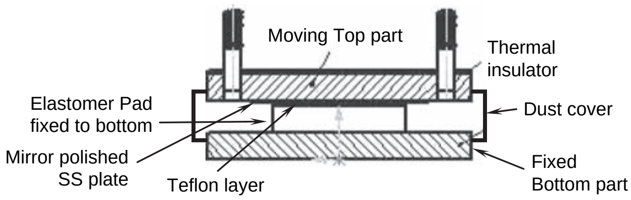

Fig. 6. Plain slide bearing.

3.2.2. Mounting the module on civil foundation permitting free thermal expansion

The modules are very large in size and heavy in weight. They are mounted on the civil foundation structure at a height of 3 m. Under normal working condition, the high temperature modules can expand up to 17 mm due to thermal expansion. If this expansion is prevented it can cause excessive loading of the civil foundation as well as the module itself. For near uniform loading of the foundation beams, the modules are supported at multiple locations. Smaller modules are supported at 16 support points and larger modules are supported at 24 support points.

The dual purpose of thermal isolation and fine leveling is achieved by mounting the modules on slide bearings designed for the purpose. The slide bearing has a fixed bottom part consisting of a rigid base and an elastomer pad topped with a Teflon layer and a moving top part consisting of a mirror polished stainless steel plate fixed to the bottom side of a rigid steel plate. The bottom part of the bearing is attached to the foundation beam, while the top part is bolted to the modules through a thermal insulator. The insulating pad thermally isolates the bearing and foundation from the module. The stainless steel to Teflon low friction pair permits free expansion of the module on the foundation. The elastomer pad takes care of unevenness in the fine range. The bearings are tested for a friction coefficient of 0.05. Fig. 6 shows the construction of a typical slide bearing.

Two bearings at the middle support locations are designed to lock the modules to the foundation and are capable of resisting the full horizontal shear, in the case of a bulk horizontal movement such as an earthquake. The bearings mounted at the end locations are also designed to resist horizontal movement of the module beyond the range of normal thermal expansion. A typical bearing-mounting plan is shown in Fig. 7.

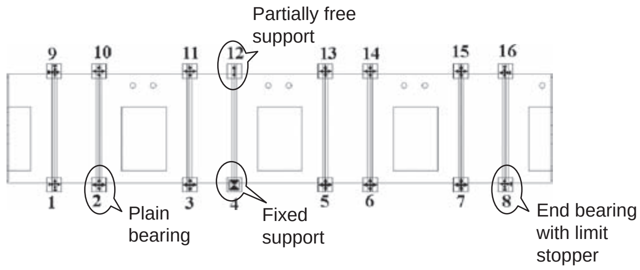

Fig. 7. Typical slide bearing mounting plan for module.

3.2.3. Interconnecting the module in the linear layout

A linear layout is adopted for the plant, wherein all the modules are arranged along a straight line. This layout has the advantage of reducing the pressure loss across stages. It also saves on the expensive cupronickel tubesheets.

In the long tube layout, each module is required to be isolated from forces generated due to thermal expansions in adjacent modules. Physical alignment of modules also becomes very important for interconnecting the module. Therefore, the modules need to be interconnected in a manner capable of absorbing thermal expansions modules as well as the reasonable level of misalignment between modules. The modules of this plant are inter-connected with each other through bellow assemblies for all the streams namely, re-cycle brine, flashing brine, product water and the non-condensable gas. Fig. 8 shows a typical interconnection between modules for re-cycle brine.

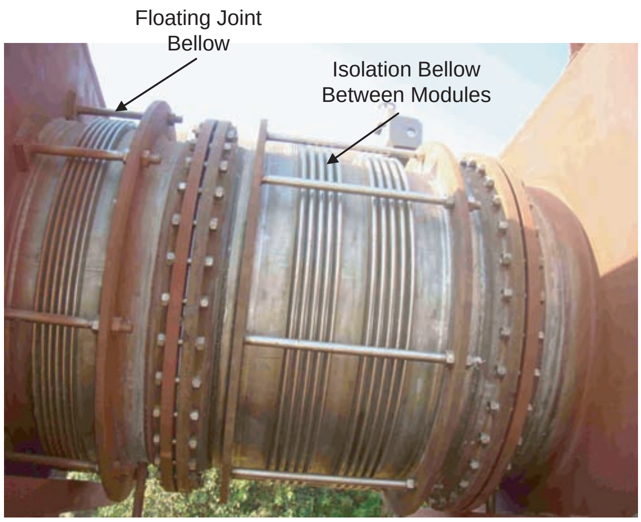

Fig. 8. Typical interconnection between modules for recycle brine.

3.3. Design for minimum leakage of vapour across stages

For high performance of an MSF plant, it is essential that the vapours produced in a stage are allowed to pass through the demister and get condensed in the segment of tube banks belonging to the same stage. It is also important that a minimum, but uniform stable level of flashing brine is maintained in all stages. However, there are several possibilities that vapours can leak across the stages, resulting lower recovery heat, which directly affect the plant performance. The main sources of leakage of vapours across stages are (a) vapour blow-through brine orifice, (b) leakages through clearances between tubes and holes in the stage partitions and (c) vapour leaving the stage uncondensed through the vent opening to the next stage. The leakages are particularly higher in the initial stages where pressure difference ΔP across the stage is high and the specific volume of the vapour is low. Some of these leakages are inevitable, but majority can be controlled proper design.

3.3.1. Leakage by vapour blow-through through brine orifice

In the plant, the design ΔP across stages vary from 1500 mm WG to 150 mm WG. To reduce leakage, a liquid seal is incorporated between stages, which is terminated at the brine orifice assembly. The depth of the liquid seal is maintained higher that the ΔP across the corresponding stages totally prevents vapour bow-through. The brine level in the stages can be maintained only if the ΔP across the stage is correctly matched. The design of the brine orifice provides for a wide range of control in the brine flow area for adjustment. The brine orifice is a sliding plate assembly, with a fixed minimum opening and certain percentages of control opening. The fixed opening is varied across the stages. Fig. 9 shows a typical arrangement of the liquid seal and the brine orifice incorporated in the flash brine route in the modules across adjacent stages.

3.3.2. Leakage through stage partition

This can be completely avoided only by putting suitable inserts between the tube and hole. However, considering the practical difficulties involved, this has not been adopted. The leakage however has been controlled by minimizing the clearance between the tube and holes by adopting very close dimensional tolerances. In the large sized modules of 11–16 m long wherein the stage partitions are 2.75–4.5 m apart with the number of baffles in between, aligning large parts with fine toleranced holes and assembling the tube bundle is however, a Herculean task. The problem is simplified by

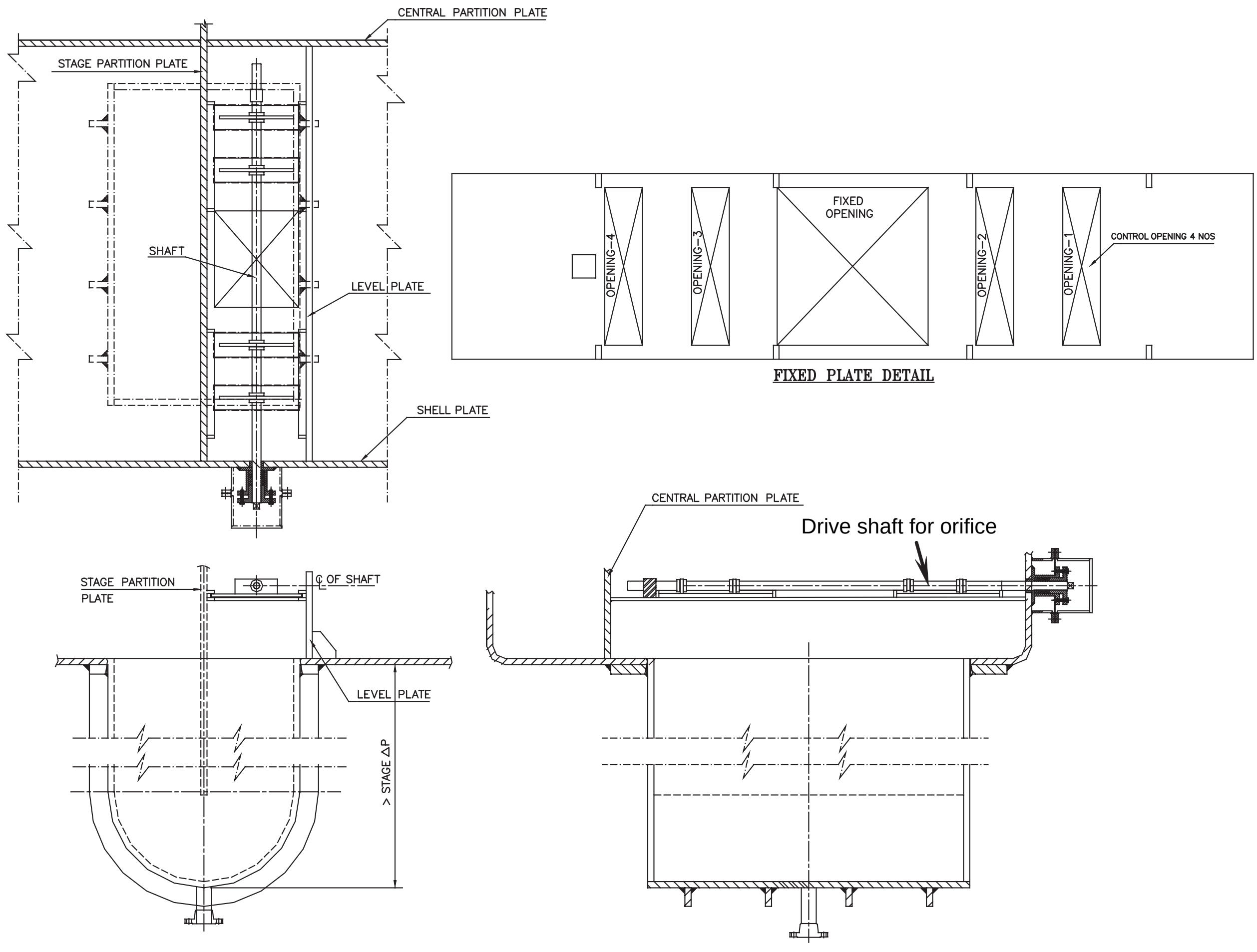

Fig. 9. Liquid seal and brine orifice.

introducing secondary tubesheets at each stage partition. The holes in the secondary tubesheets are drilled and reamed to the same tolerances as that of the main tubesheets. The secondary tubesheets, which are smaller in size, can be perfectly aligned with other tubesheets and baffles by conventional methods with relative ease. After aligning, the secondary tubesheets are welded to the stage partition plate. Through secondary tubesheets, the clearance between the holes and tubes are minimized and thus our modules are designed to achieve very low leakage through stage partitions. Fig. 1 shows the construction with secondary tubesheets.

3.3.3. Leakage through vent opening

The third source of leakage is directly through the vent opening, through which uncondensed vapour can leak to the next stage. This is particularly relevant to our modules, where we have accommodated a circular tube bundle in a rectangular space. Near the vertical walls of the rectangular space, the vapour will find only fewer tubes. In addition, certain minimum space has to be left for providing access for fabrication activities. Thus the vapours get a low resistance path through near the vertical walls to vent opening bypassing the tube bundle. We have removed this low resistance path by putting a pair of the reflector plate between the tube bundle in each segment as shown in Fig. 11. This is expected to improve the performance of the tube bundle and reduce the leakage through vent opening.

4. Materials of construction

The module shell and other major internal parts are made of boiler quality carbon steel plates. This is a very conscious choice made, in spite of the corrosive atmosphere, out of economic considerations, by providing adequate corrosion allowances for general corrosion. The use of carbon steel as major material

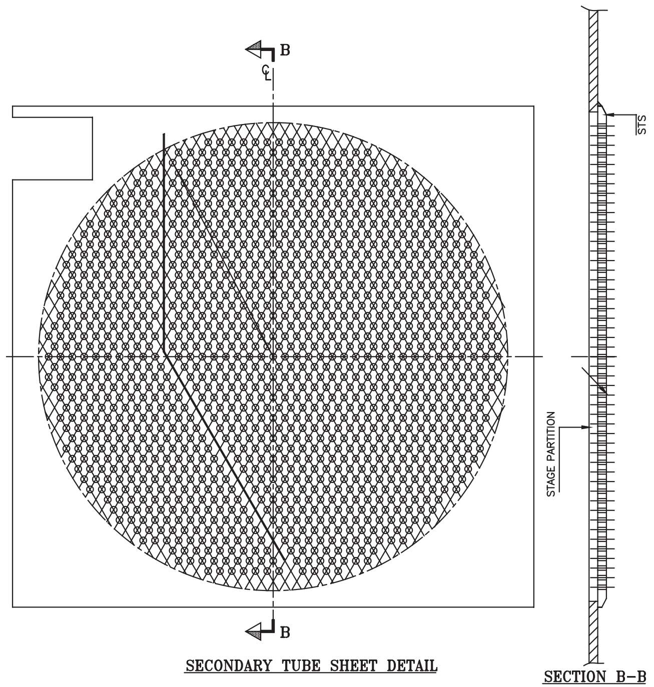

Fig. 10. Secondary tubesheet help reducing the leakage across stage partition.

of construction is made possible by the pre-treatment given to seawater wherein complete carbon dioxide and oxygen are removed by vacuum de-aeration. The oxygen level in the brine is brought down to less than 20 ppb. For tackling the general corrosion a corrosion allowance of 10 mm has been provided on the chamber walls.

The tubes and tubesheets are constructed out of 90:10 cupronickel alloy considering its corrosion resistance and thermal properties.

All nozzles and other parts, where providing adequate corrosion allowances are not feasible, are constructed out of SS316L. Care has been taken to avoid stagnant pockets of brine in the SS 316L parts to reduce pitting corrosion.

Wherever SS316L is joined to a CS part, care has been taken to ensure that the area available on the CS parts is far more than that of SS parts to reduce galvanic corrosion. Further all joints between CS and SS in contact with brine were welded with nickel base filler materials such as inconel. The brine orifice and butterfly valves are also made of SS 316L.

The large isolation and expansion joint bellows are made of inconel based on its superior erosion resistance and formability. The main isolation bellows are additionally fitted with erosion guards. Isolation bellows in the product and non-condensable gas streams are made of SS 316L. All fasteners used in the module are of SS316 material.

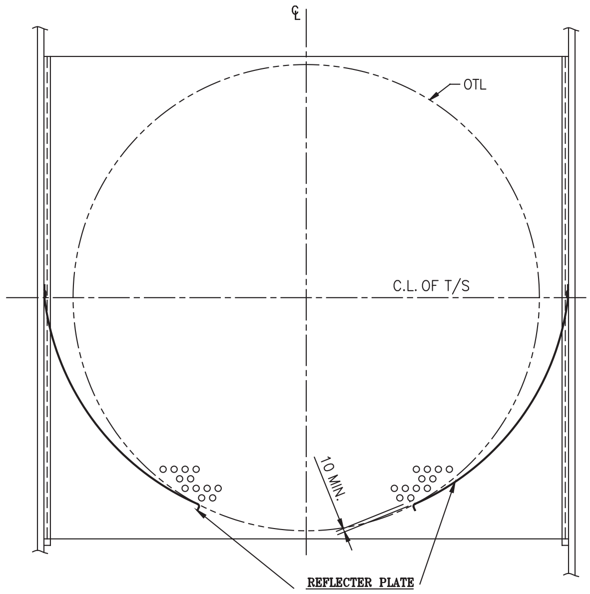

Fig. 11. Reflector plate increase resistance to vapor leakage to vent.

There are several dissimilar metal joints in the module, which are unavoidable. A dissimilar metal joint in a corrosive medium runs the risk of galvanic corrosion unless the ratio of the area of the nobler metal to the area of the less noble metal is properly matched with reference to the corrosion potentials. This factor has been considered while designing the dissimilar metal joints in the module.

5. Module construction

This MSF plant of long tube design has been a first of its kind in our country. As such its construction, especially the construction of the MSF modules had thrown many challenges in the beginning. We share some of these experiences in the following paragraphs.

5.1. Full-scale solid modeling

The complex geometry, multiple partitions within the module, restricted access for critical fabrication activities, accurate mounting requirements, etc, made sequencing of the activities very important. We started off with a full-scale solid modeling of the plant complete with minute details. This has given an in-depth understanding about the whole job. The foundation layout, support locations, inter-connection cutouts were all derived accurately from these solid models. The efforts have paid off well by facilitating a smooth mounting, alignment and inter connection of the modules despite the massive size and complex design.

5.2. Mock-up module

It was mentioned earlier that corner joints have been avoided in the module. On the construction side this called for cold forming of geometrically correct shapes out of thick steel plates. Sharp bending of plates generated residual stresses, making stress relieving of the module essential. Each module has four stages. Product barrier and demister pads further sub divided each stage. The condenser tube bundle runs through all the stages on the product side. In order to avoid any melt through of the thin tube, all welding activities to be completed before loading the tubes in the module. The fixed tubesheet in the module is welded to the module end cover. This dissimilar metal joint between carbon steel and cupro-nickel had to be done in position. Because of the large size and weight, the modules were to be fabricated and erected in-situ on the open site near sea. Considering all these before going for the actual module, we constructed a full section mockup module covering the most intricate aspects of the actual module and working space constraints during tube loading.

The experience of the mockup module has been invaluable and has helped solving many problems beforehand. It has helped establishing a safe and elaborate assembly sequence that has generally been followed till the last module. It has brought out the danger of header distribution of flue gases for heat treatment, where the header pipes melted before achieving the temperature. Based on this feedback, individual burners and distribution pipes were used for each compartment in the module. This helped reducing the heat loss and reduced the cycle time. The end cover to tubesheet joints in the mockup initially revealed serious crack defects. This led to a thorough review of the welding procedure. We could not have afforded a similar failure in a module joint. Split secondary tubesheet was introduced on the stage partition plate for better alignment and tolerance control.

5.3. Stress relieving of the modules

After structural fabrication but before assembly of the tube bundle, the modules were subjected to a stress relieving cycle in position. This was done by insulating the module with ceramic wool all over and burning high-speed diesel in a controlled manner. Stress relieving of the mockup module was tried with two burners and distributing the flue gases through headers as shown in Fig. 12(a). However this was unsuccessful in the first instance as the desired temperature could not be reached due to heavy heat loss from the header pipes at higher temperature. The arrangement was reviewed and the header distribution was completely avoided by using individual burners for each compartment as shown in Fig. 12(b). With multiple partitions, achieving temperature uniformity across the module has been quite difficult. Temperatures were monitored as 36 locations to ensure a temperature distribution as uniform as possible.

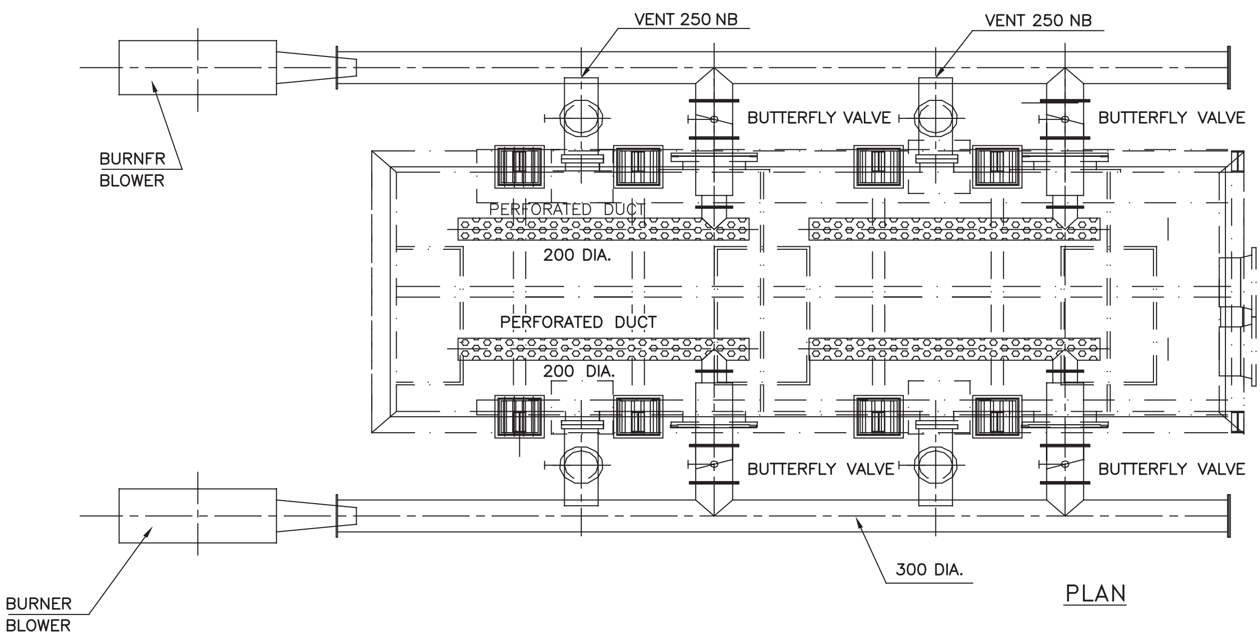

Fig. 12(a). Initial arrangement for stress relieving of mockup module.

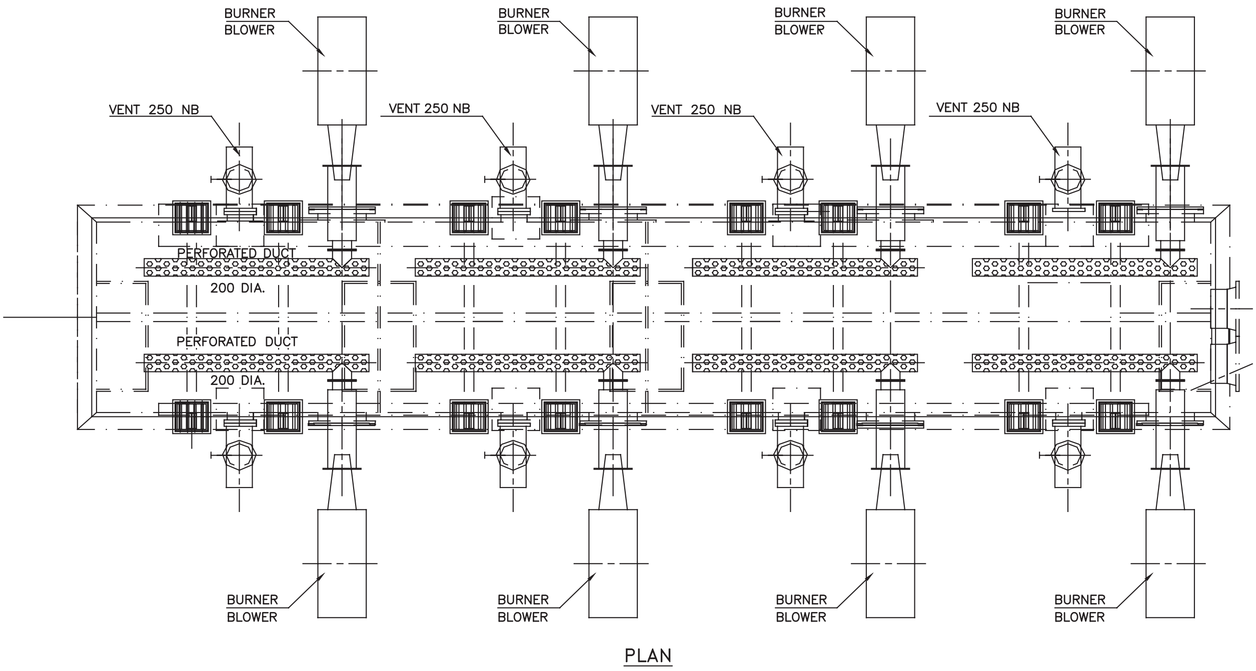

Fig. 12(b). Revised arrangements used for module stress relieving with individual burners for each chambers.

5.4. Tubesheet (Cu:Ni) to end cover(CS) dissimilar metal joint

The joint between 50–60 mm thick Cupronickel 90:10 tubesheet and 38–50 mm CS end cover of the module is another important aspect which we feel worth mentioning here. The joint had to be welded from both side with very restricted access from inside. Considering the restrictions, welders were qualified for 6GR position as per API standards. The joint was initially tried in the mockup with single layer buttering of inconel 82. However both tubesheet joints in the mockup revealed huge cracks.

This resulted in a thorough review of joint design, welding filler materials and heat control. A double layer buttering with nickel and monel followed by welding with Cu:Ni filler materials (Fig. 13) was adopted after detailed trials and metallographic studies. Interpass temperature of 65 °C was strictly followed. To be on the safer side, a layer-by-layer radiography of the weld deposits was taken to rule out growth of any defects inside the joint.

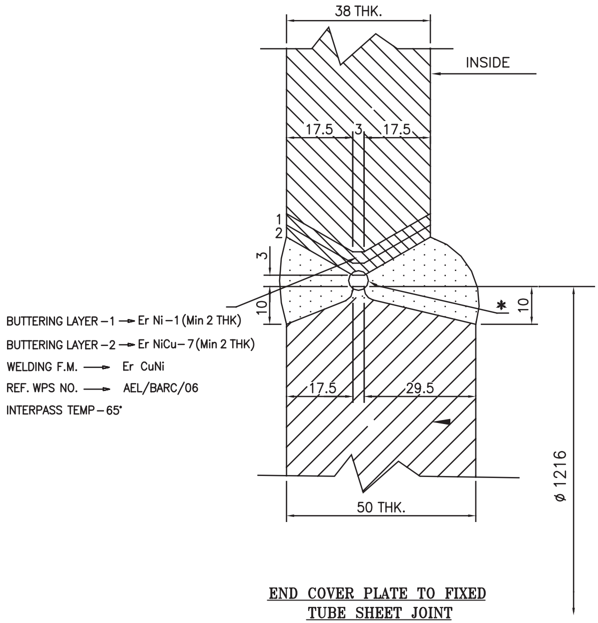

Fig. 13. End cover plate to fixed tube sheet joint.

5.5. Erection sequence

The linear layout of the plant has put the modules one after the other in the longitudinal direction. Modules have lengths varying from 11.5 m to 16 m. Till the tube loading is completed in one module, fabrication activities of the next module in the linear layout could not be taken up beyond a certain stage, considerably hampering the progress of the project. To tide over the situation, every third module has been fabricated outside the original foundation on temporary structures (Fig. 14). These modules were mounted in place after the tubing is completed, using

Fig. 14. A view of the module train during construction.

Fig. 15. One of the modules being lifted to mount in position.

heavy-duty cranes (Fig. 15). This has considerably saved the construction time.

6. Conclusion

The MSF module train is an interesting piece of engineering equipment for a mechanical engineer. Its design and site construction has thrown up many challenges at various stages. The authors could arrive at practical solutions for all problems and satisfactorily complete the module train. However, there are lots of scopes for further improvement in the modules. The module geometry and internal layout can be optimized to reduce the cost of construction as well as overall footprint of the modules. Major dissimilar metal joints between the module end cover and tubesheet can be re-designed to substantially reduce the heat input and residual stresses with better access for weld deposition. Feedbacks from the first hand experience of design and construction of the module train will definitely aid installation of better plants in future.

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