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# DEVELOPMENTS IN FALLING FILM TYPE (DOWNFLOW) REBOILERS IN THE AIR SEPARATION INDUSTRY

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## ABSTRACT

Main condenser/reboilers in an air separation plant thermally link the low and high pressure distillation columns. They provide vapor boil-up to the low pressure column and reflux liquid to both columns. The thermal performance of the main condenser/reboiler is critical to the overall energy efficiency of the air separation process. Even though main condenser/reboilers are operated both in the thermosyphon and downflow configurations, increasing energy costs have favored the latter. Significant developments have taken place in falling film or downflow main condenser/reboilers that promote their use in the air separation industry. This paper addresses three key areas of their development (i) the type of downflow main condenser/reboilers and their mode of operation, (ii) specification of minimum liquid flowrate for adequate wetting of heat transfer surfaces in the vaporizing passages, and (iii) developments in the flow distributor design. It is shown that successful and safe operation of main condenser/reboilers requires a good insight into these areas in optimizing their performance for low product cost.

## INTRODUCTION

A flowsheet for a typical air separation plant producing oxygen, nitrogen and argon is shown in Figure 1. The main condenser/reboiler lies at the heart of the process and is located at the base of the upper (or low pressure) distillation column. Its function is to condense nitrogen from the lower (or high pressure) column at about 5.2 bar, and to vaporize the liquid oxygen which descends from the upper column at about 1.3 bar. The thermal performance of the main condenser/reboiler is critical in minimizing the power consumed by the compressor which feeds air to the plant. An increase in the temperature difference between the condensing and vaporizing streams across the exchanger of only 0.1K for example, results in an increase in power of about 0.5%. This can be very significant for large plants.

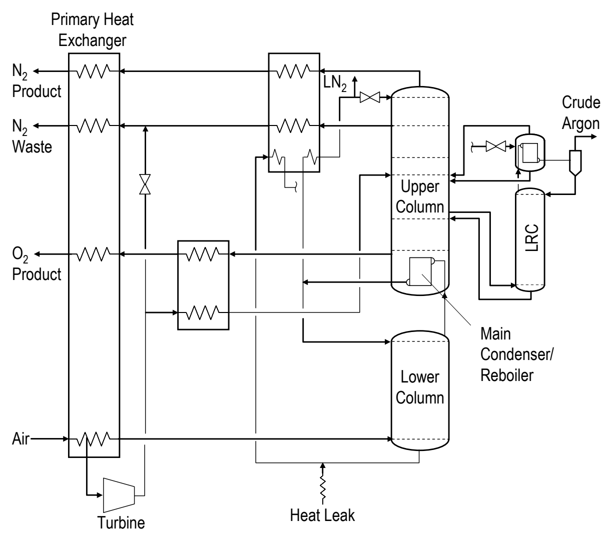


***Figure 1. Air Separation Plant Flowsheet***

Thus, main condenser/reboilers have been the subject of several studies in the air separation industry resulting in significant development over the past decades.

## TYPES OF DOWNFLOW MAIN CONDENSER/ REBOILERS AND THEIR MODE OF OPERATION

Main condenser/reboilers are designed as either brazed aluminum plate-fin heat exchangers (BAHX) or aluminum shell-and-tube heat exchangers. Schematics of the two types are shown in Figures 2 and 3. In the BAHX, corrugated fins sandwiched between the parting sheets provide high surface area per unit volume. They also result in small hydraulic diameter passages. BAHX main condenser/reboilers are extensively used in the air separation industry. Although Praxair has used the BAHX design in some plants, a patented (Smolarek, 1984), doubly enhanced tube version of the shell-and-tube heat exchanger is preferred. Enhancement for condensation is provided by longitudinal flutes on the outside of tubes and by a porous (Highflux) surface on the inside of the tubes for boiling (as shown in Figure 4). Even though the shell-and-tube configuration has less surface area per unit volume, the doubly enhanced tubes typically transfer 300 $kW/m^3K$ versus 250 $kW/m^3K$ for a BAHX (Lockett and Srinivasan, 1993). These units operate in a vertical orientation either in the thermosyphon mode or in the falling film mode. Operation in the falling film mode results in smaller temperature differences between the nitrogen and oxygen streams.

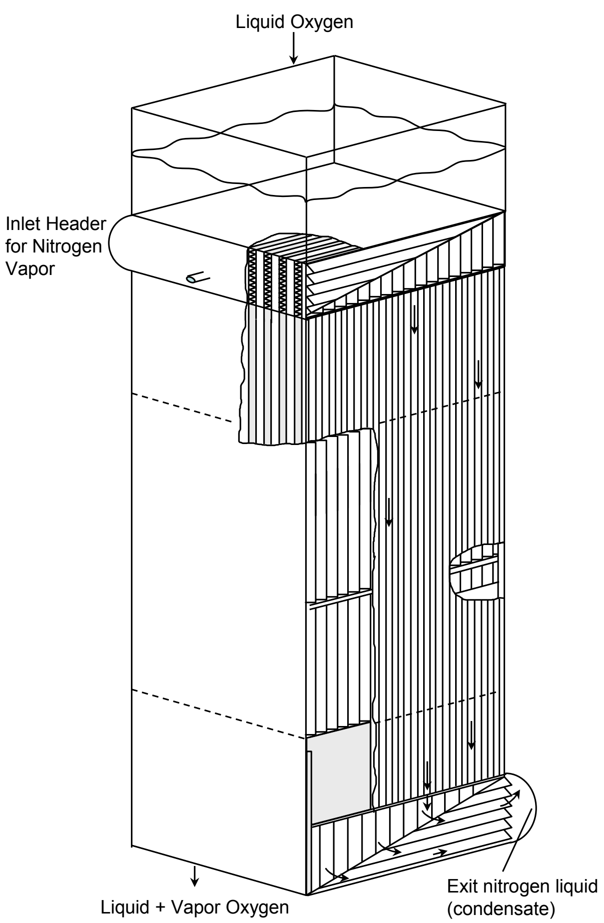


*Figure 2. BAHX – Downflow*

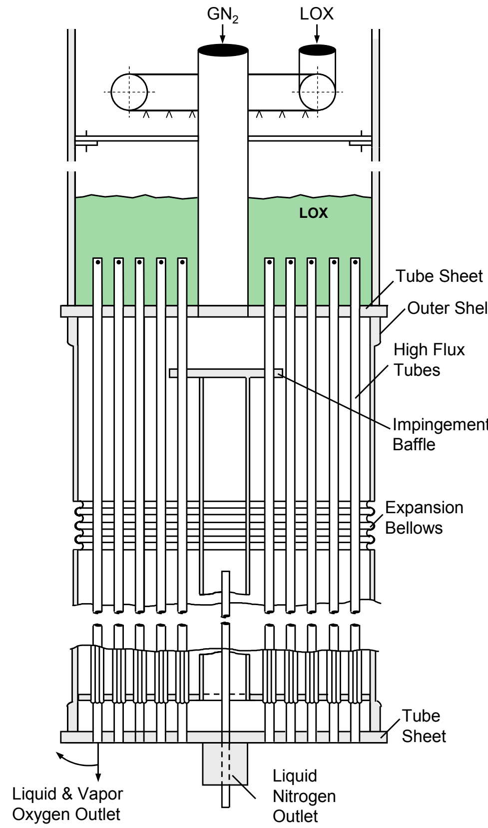


*Figure 3. Shell-and-Tube Downflow*

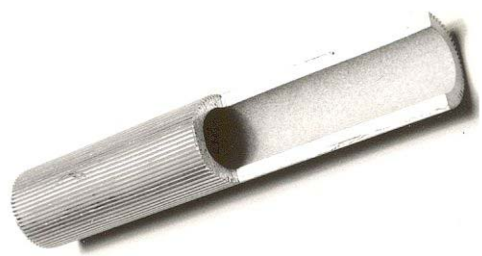

*Figure 4. Doubly Enhanced Tube*

## DOWNFLOW REBOILER – ONCE-THROUGH VS. RECIRCULATING

In a falling film or downflow reboiler, the liquid to be vaporized flows through the heat transfer tubes or passages from top to bottom of the exchanger. Gravity drives the flow. The flow to each tube or passage is delivered by flow distributors located at the top. Downflow type reboilers can be used for main or auxiliary vaporizers in an air separation plant.

There are two configurations of downflow reboilers, “once-through” and “recirculating” (CGA document, 2000).

1. **Once-Through** reboiler cores, as shown in Figure 5, are fed only with reflux liquid directly from the packing or trays of the low pressure distillation columns (Swaminathan et al., 1992). The flow to the reboiler is a function of the L/V ratio (liquid to vapor mass flow rate ratio) just below the lowest packing or tray of the column.

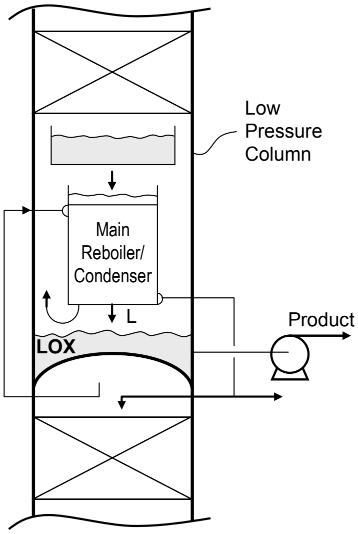


*Figure 5. Once-Through Downflow Reboiler*

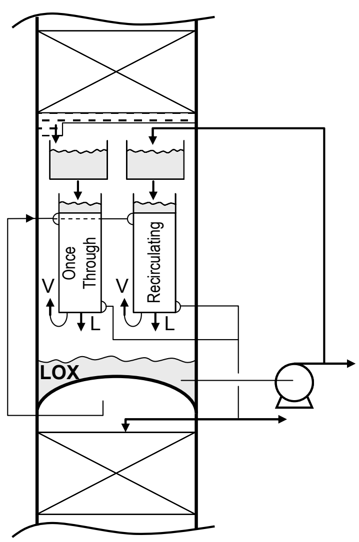


*Figure 6. Recirculating Downflow Reboiler (Option 1)*

2. **Recirculating** reboiler cores are fed with liquid using one of the following arrangements:
   a. They are fed with liquid from the sump of the column that has already been passed through a once-through core (VanHardeveld et al., 2001). This arrangement is shown in Figure 6.
   b. As shown in Figure 7, they are fed with liquid that is a combination of the direct reflux fed from the packing/trays and the recirculated liquid from the sump of the column (Lockett and Srinivasan, 1997).

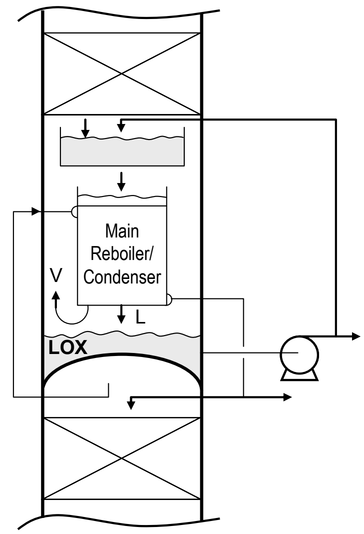


*Figure 7. Recirculating Downflow Reboiler (Option 2)*

   c. The direct reflux from the packing/trays bypasses the downflow main condenser and is collected in the sump of the low pressure column. This liquid, along with the recirculating liquid, is circulated through the reboiler (Lockett and Srinivasan, 1997). This arrangement can be seen in Figure 8.

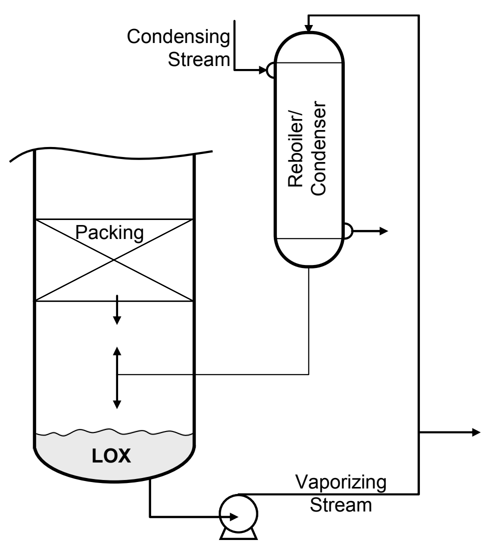


*Figure 8. Recirculating Downflow Reboiler (Option 3)*

In all the above recirculating alternatives, the circulation of liquid from the sump to the reboiler requires a recirculation pump.

In the once-through, as well as in the recirculating downflow reboiler, vaporized oxygen flows from the bottom of the exchanger core along with the excess liquid. The flow rate of the excess liquid is kept at or above a minimum rate.

**Design Considerations - Minimum Liquid Flowrate**

The minimum liquid flowrate on the reboiler heat transfer passages is specified by taking into account the following considerations.

1. Prevent breakdown of the liquid film so that the heat transfer surface area is effectively utilized in forced convective evaporative or boiling heat transfer. Unwetted regions lose their effectiveness in terms of heat transfer to the vaporizing stream.
2. Ensure that the maximum contaminant content, especially safety-related hydrocarbons, in the unvaporized liquid oxygen does not reach dangerous levels. The hydrocarbon concentration in the liquid oxygen increases progressively as the oxygen vaporizes in the heat transfer passages.
3. Minimize fouling (deposition of solids, contaminants such as $N_2O$, $CO_2$, etc.) by ensuring adequate wetting of the boiling surfaces. Fouling is also minimized by keeping the concentration of the contaminants in the liquid well below their solubility limits.

Thus, from the aforesaid considerations, the specified liquid flowrate must result in a stable liquid film on the boiling surface to ensure adequate wetting. It should stay above a minimum threshold to prevent the breakdown of the liquid film. It is also a function of the reboiler geometry – particularly the heat transfer surface area and the resulting flow perimeter. Equations for predicting the minimum liquid flow rate to prevent film breakdown are based on the flowrate per unit width ($\Gamma_L$). A film Reynolds number, $Re_L$ is defined and it is related to the flowrate per unit width as follows:

$$Re_L = \frac{4\Gamma_L}{\mu_L} \qquad (1)$$

where: $\Gamma_L$ is the liquid flowrate per unit width of the heat transfer surface ($kgs^{-1}m^{-1}$)
$\mu_L$ is the liquid viscosity ($Nsm^{-2}$)

The breakdown of the liquid film is a surface phenomenon and therefore the surface tension and the angle of contact play an important role in the determination of the minimum film Reynolds number. Correlations based on experimental data express $(Re_L)_{min}$ as a function of surface tension, contact angle and other properties of the fluid (For example, see Mikiekewicz (1976)).

Alternatively, the minimum liquid flow rate to ensure adequate wetting can also be expressed as a dimensionless ratio L/V (liquid-to-vapor mass flowrate ratio) at the exit of the boiling passages. This method does not explicitly take into account the surface area and geometry of the reboiler/main condenser. Therefore, recommendations based on L/V are restricted to a specific type of reboiler/main condenser and also for typical ranges of operating conditions encountered in air separation units.

The relationship between the liquid to vapor mass flowrate ratio L/V, the Reynolds number $Re_L$ and flow width (or perimeter) of the heat transfer surface W is given by:.

$$\frac{L}{V} = \frac{\left[Re_L\right] W \mu_L}{4 \dot{M}_V} \qquad (2)$$

where: $\mu_L$ is the dynamic viscosity, $kgm^{-1}s^{-1}$
$\dot{M}_V$ is the vapor mass flowrate, $kgs^{-1}$
W is the wetted perimeter, m

For a group of shell-and-tube modules

$$W = N_t N_m \pi Di \qquad (3)$$

where: $N_t$ = number of tubes per module
$N_m$ = number of modules
Di = inside diameter of the tube, m

For a group of BAHX module cores

$$W = N_p N_m \left[2w\left\{1+N_f h_f\right\}\right] \qquad (4)$$

where: $N_p$ = number of layers for the vaporizing stream per BAHX
$N_m$ = number of BAHX cores
$N_f$ = number of fins per meter for unfinned BAHX (=0), $m^{-1}$
$h_f$ = height of fin, m
w = width of layer, m

Air separation companies have addressed the question of the minimum liquid flowrate separately for the plate-fin BAHX and shell-and-tube Highflux main condenser/ reboiler. Also, even for a given type of condenser/reboiler one may choose to work with $Re_L$ vs. L/V.

***Plate-fin BAHX geometry***. Heat transfer passages in a plate-fin BAHX have non-circular geometries. In such geometries liquid has a tendency to be drawn into corners resulting in non-uniform film thickness around the perimeter of the passage. Therefore the minimum liquid flowrate required for complete wetting of the heat transfer surface is generally higher for non-circular geometries than for a plain surface or a circular tube.

We studied the wetting characteristics of plate-fin passages using a representative test section of a downflow plate-fin type reboiler. Two-phase downflow at various liquid to vapor fractions was maintained in the test section by circulating liquid refrigerant (R141b) and gaseous nitrogen at appropriate flowrates. The safe operating regimes and minimum liquid flow rates were determined by observing the flow patterns under various liquid and gas mass flow velocities. A flow pattern map was constructed using the momentum fluxes of the liquid and vapor as coordinates. It is shown in Figure 9. $G_L$ and $G_V$ are mass velocities of the liquid and vapor phases, respectively. $\rho_L$ and $\rho_V$ are the density of the liquid and vapor phases, respectively.

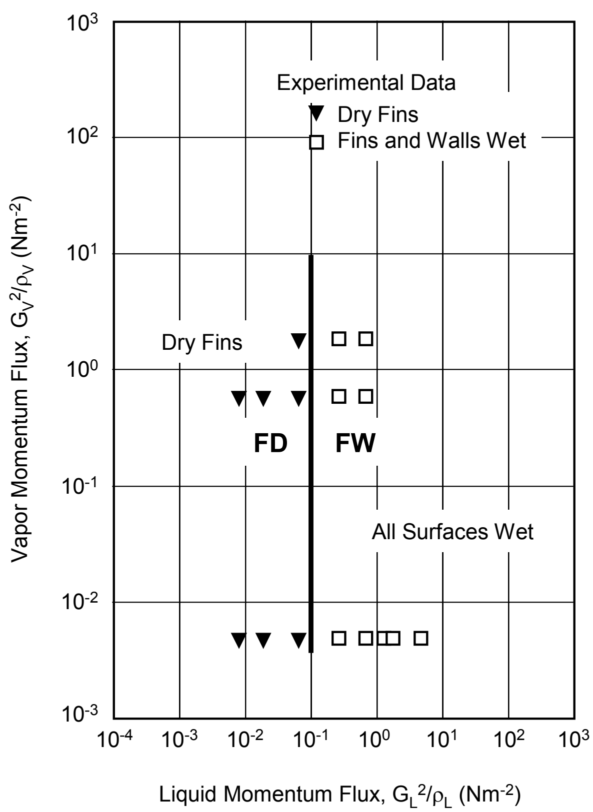


***Figure 9. Fin Dryout Regime Map – Two-Phase Downflow***

The flow pattern map enables the selection of a liquid mass flux in the downflow reboiler that will prevent dry patch formation on the heat transfer surfaces. Of significance to downflow reboiler operation is the demarcation line between the fin dryout regime and the fully wet regime (shown by the solid bold line in Figure 9). This line defines the minimum liquid mass flux required to prevent fin dryout. It is seen that the liquid momentum flux to prevent dry out is a constant for the range of vapor flux shown in Figure 9. However, the minimum liquid momentum flux required to prevent dry out increases for higher vapor flux (exceeding 10 Nm$^{-2}$). This data for higher vapor flux is not shown in the figure. Any flow condition that falls on the region shown as FD, results in dry fins. Similarly, flow conditions falling in the region shown as FW result in completely wet heat transfer surfaces. To illustrate the use of this map: for any value of the vapor momentum flux $\left(G_V^2/\rho_V\right)$, in the range 0.005 to 10 Nm$^{-2}$, the minimum liquid momentum flux required $\left(G_L^2/\rho_L\right)$ is 0.1 Nm$^{-2}$. For liquid oxygen at 1.6 bar, the corresponding value of $G_L$ is ~11.0 kgm$^{-2}$s$^{-1}$. In terms of the Reynolds number, $Re_L$ = 150 (for an hydraulic diameter of 2.5 mm for the plate-fin geometry used in the experiments - 550 fins per meter, 6.35 mm fin height, 5% perforated).

Swaminathan et al., 1992, provide information on the minimum liquid flow rate required in reboilers with plate-fin geometries. They recommend a minimum $Re_L$ of 20 and a preferable range between 50 and 300. The same patent also recommends a maximum of 1000. The basis for their criteria can be inferred from a paper by Houghton et al. (2000). The important findings of this work are as follows:

- The deposition of contaminants on the boiling surface is strongly influenced by the concentration of the precipitating component in the liquid.
- The liquid flowrate and reboiler exit $Re_L$ did not have a strong influence on the accumulation rate for a fixed exit concentration.
- Maintaining low contaminant concentrations (low $N_2O$ concentration) in the reboiler liquid is the key to minimizing accumulation.

In their pilot plant and field tests (Houghton et al., 2000), deposition of contaminants ($N_2O$) was found to occur on the boiling surfaces even at low concentrations relative to the liquid solubility. This was explained by assuming the existence of partial dry out regions in the heat transfer passages. In a non-circular duct, such as in a BAHX, surface tension forces can cause the formation of dry spots on the heat transfer surfaces. However, by maintaining low concentrations of the contaminants in the liquid and following recommendations on defrost intervals, downflow reboilers can be operated safely.

***Shell-and-tube geometry.*** Mikiekewicz and Moszynski (1976) provide the following equation for predicting the minimum Reynolds number for adequate wetting inside a smooth circular tube.

$$Re_{min} = 4\left(\frac{\sigma^3 \rho_L}{\mu_L^4 g}\right)^{1/5} f(\theta)$$

The function f(θ) is presented graphically where θ is the contact angle. If we assume a contact angle of 20° for liquid oxygen, then from the equation of Mikiekewicz (1976) the minimum Reynolds number to prevent film breakdown is 110. Using the method of Hartley (1964), the predicted Reynolds number to prevent film breakdown is 375. Since, Highflux porous surfaces have better wetting characteristics the use of smooth tube predictions may be conservative.

Highflux modules are made in standard sizes. The number of modules that are employed in a given plant depends on the heat load and the temperature difference between the condensing (or nitrogen) stream and the vaporizing (oxygen) stream specified by the process. Smaller temperature difference would require more modules and the liquid flow is distributed to a larger number of tubes. In air separation units using downflow modules the temperature difference can range from 0.5 K to 1.5 K. Thus, to operate the main condenser/reboiler over this range of temperature difference and to ensure adequate wetting, Lockett and Srinivasan, 1997, recommend a minimum L/V of 0.5 and a preferable range of 1.0 to 4.0 at the exit of the heat transfer passages.

**Design Considerations – Flow Distribution**

Of all the areas, the flow distribution is perhaps the most critical element in the development of falling film or downflow main condenser/reboilers. Not only is an even flow of liquid through each tube or plate-fin passage essential to guarantee the heat exchanger's thermal performance, but it also must satisfy the minimum liquid flow requirement for each passage. Maldistribution can cause dry patches to form in some tubes/passages while other tubes/passages carry excess amounts of liquid. It is also necessary that the liquid supplied to each tube is distributed uniformly around the periphery of the tube or the width of the plate-fin passage. These are some of the challenges of flow distribution and are addressed as follows:

***Plate-Fin Brazed Aluminum Heat Exchanger (BAHX):*** The purpose of the flow distributor is to provide a good (or uniform) distribution of fluid across the width of each layer of the plate fin heat exchanger. The fluid enters the heat exchanger as a single phase medium. Evaporation occurs within the plate fin passage. Generally, the single-phase fluid is introduced and removed by means of headers attached to the ends or sides of the heat exchanger block. These headers may cover the entire (or whole) width and length of the core in which case the stream can flow into the width of each passage. In air separation main condenser/reboilers, the inlet is generally an open tank (shown in Figure 2) or alternatively, it is a dome header.

Once the fluid reaches the entry header tank, it is necessary to distribute the fluid to the whole of the flow area. This is achieved by one of the following methods:

1. Sparger tubes
2. Distributor finning
3. A combination of (1) and (2).

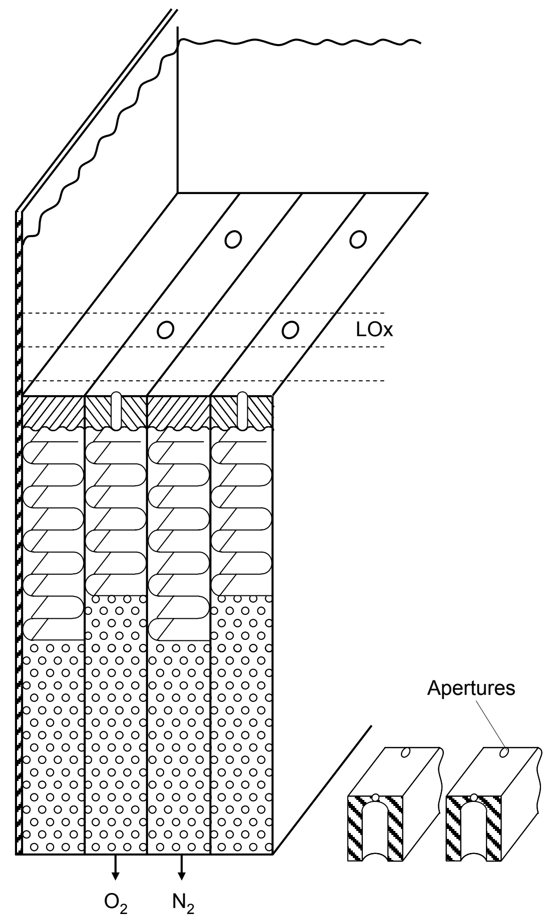


***Figure 10. Flow Distribution Technique Employed by Petit et al. (1986) (Design 1)***

Petit et al. (1986) describe a plate fin array configuration for use as a downflow main condenser. The oxygen liquid is distributed to the plate fin passages in two stages. The first state consists of a rough predistribution of liquid throughout the length of the plate fin passages using the arrangement shown in Figure 10. In this arrangement the oxygen passages above the predistribution plates are used as reservoirs for oxygen liquid. The liquid oxygen enters the oxygen passages through apertures provided on the perforated plates (shown in Figure 10). The liquid oxygen predistributed this way reaches the zone where hardway fins (packings) are located. These hardway fins ensure a fine distribution throughout the length of the oxygen passage. It is interesting to note that the heat exchange between the oxygen and the nitrogen starts during the passage of liquid oxygen through the hardway fins. Serrated fins are used as hardway fins.

In the same work by Petit et al. (1986), as an alternative to the above arrangement and in order to accommodate withdrawal of gaseous oxygen from the top, the following distribution mechanism was adopted. In this arrangement, the nitrogen passages above the nitrogen entry point are used as reservoirs for oxygen liquid. The liquid oxygen enters the oxygen passages (which are closed at the top) from the side through apertures provided on the partition sheets. In each oxygen passage the hardway fins are eliminated. The jets of liquid oxygen issuing from the apertures strike the confronting partition plate and spread over the latter. The spacing and diameter are so chosen that the sheets of parabolic shape thus formed join into a continuous sheet a little above the thermal exchange section. Thus the oxygen is still predistributed by the apertures while its fine distribution is ensured by the partition plates themselves. The partition plates are horizontally ribbed to improve spreading. These are shown in Figure 11.

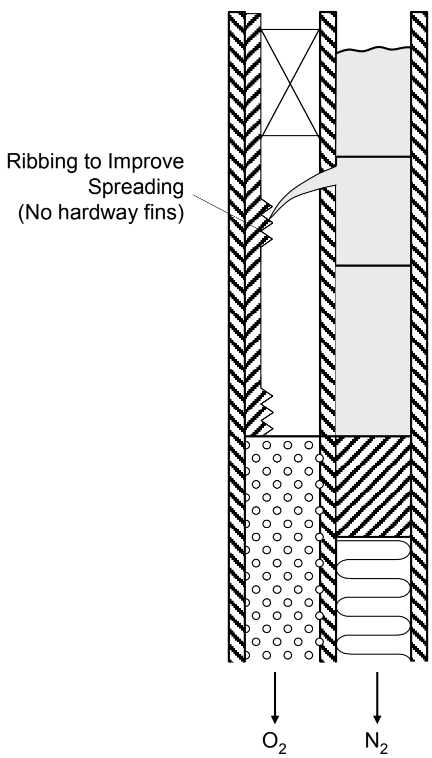


***Figure 11. Flow Distribution Technique Employed by Petit et al. (1986) (Design-2)***

The flow distribution technique used by Swaminathan et al. (1992), is shown in Figure 12. The flow distribution is achieved in two stages. The predistribution stage consists of a plurality of perforated sparger tubes located along the length of the oxygen passages. There are three vertical layers of sparger tubes for each passage of oxygen. Sparger tubes originate from headers placed at opposite ends. The fine distribution is achieved through hardway finning. The hardway finning is designed to have an effective resistance to flow in the across fin direction to allow for flow in the along fin direction so that during operation of the heat exchanger, the liquid film on the hardway finning occupies at least 25 to 50% of the void space of the hardway finning. To accomplish this liquid retention, perforated finning is employed as hardway finning. The oxygen in the hardway fin region does not exchange heat with nitrogen.

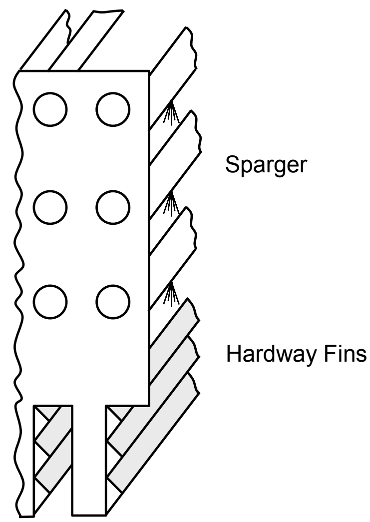


***Figure 12. Flow Distribution Device Employed by Swaminathan et al. (1992)***

Another arrangement suggested by Beduz and Scurlock (1991) is shown in Figure 13. The liquid is sprayed on to the partition plates. Due to the porous nature of the surface, the liquid oxygen spreads uniformly. The patent does not provide any detailed description of the technique used.

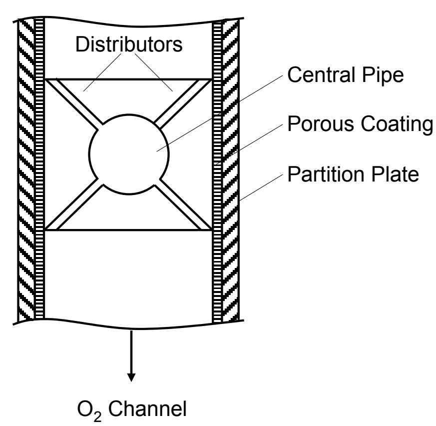

***Figure 13. Flow Distribution Device Employed by Beduz et al. (1991)***

We have experimentally investigated a number of flow distribution techniques for plate-fin layers using refrigerant R113. Various two-stage liquid distribution techniques were tested. The primary stage included (i) spargers, (ii) circular orifices in partition plates (side entry), (iii) slots in partition plates (side-entry) and low percent (5 to 10%) perforated hardway finning. The secondary stage distribution was achieved through the use of one of the following techniques: (i) hardway finning, (ii) texturized surface, and (iii) serrated main fins. Several different combinations of the primary and secondary stage distribution devices were tested.

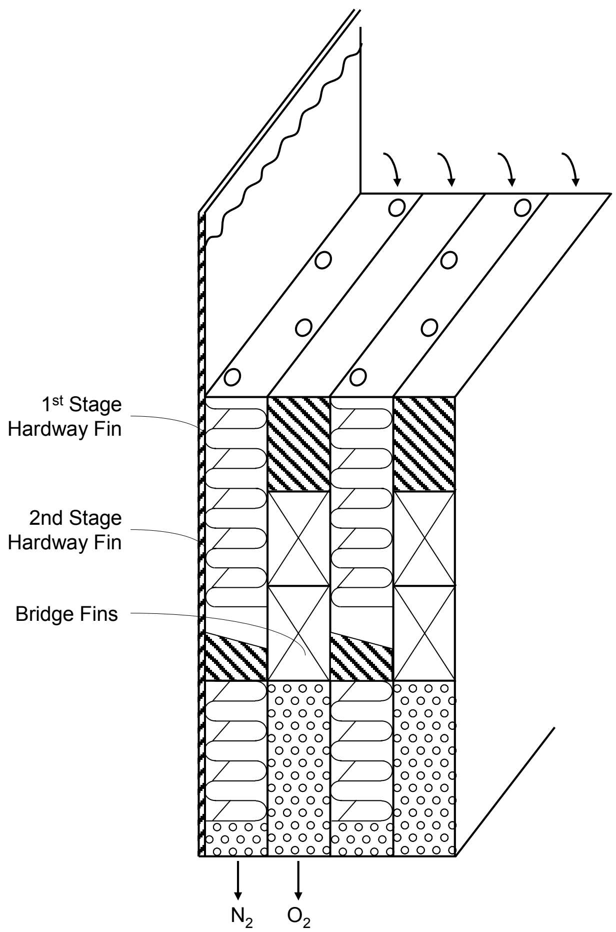


***Figure 14. Flow Distribution Technique Employed by Srinivasan et al (1995)***

The use of two-stage hardway fins gave the best performance. The primary distribution was achieved through 5% perforated hardway fin and the secondary distribution was achieved through 25% perforated hardway fin. The details can be found in Srinivasan et al., 1995. The patent also provides details of the preferred perforation patterns on the hardway fin for achieving uniform distribution. One of the preferred options of the distribution technique described in the patent is shown in Figure 14. Here the liquid oxygen enters through the condensing ($N_2$) layers at the top where the two-stage flow distribution device is located. The well distributed liquid is deflected into the vaporizing ($O_2$) layers by a sloping sealing bar that serves to isolate the condensing and vaporizing stream. The quality of the distribution is maintained with the help of bridge fins that are located in the vaporizing layers.

***Shell-and-Tube Heat Exchanger:*** Typically the liquid that enters the heat exchanger collects in a trough (forming a small reservoir of liquid) located above the tube bundle. The distributor acts as a link between the pool of liquid and the individual tubes. The gravitational head in the reservoir provides the force for driving the flow through the distributor. The flowrate through the distributor is governed by the depth of liquid covering the distribution device.

Flow distribution devices described in the literature can be broadly classified into three types: weirs, circular or annular shaped orifices, and annular shaped flow restrictors which restrict the flow over an appreciable length (e.g., see Bromley and Read, 1970 or Beccari et al., 1979).

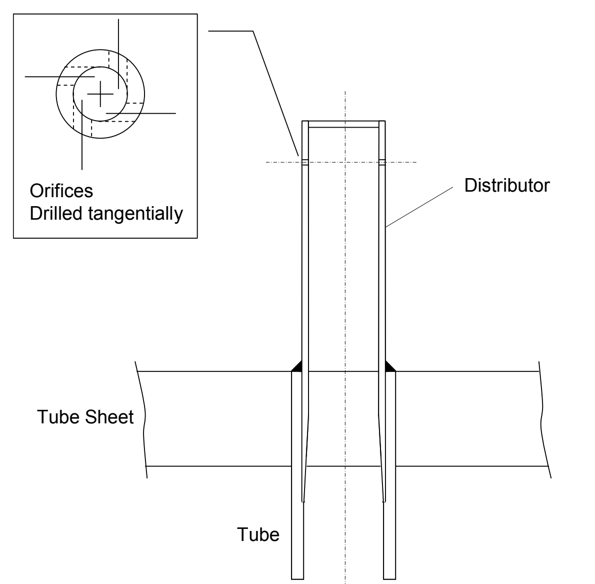


***Figure 15. Flow Distribution for Highflux Shell-and-Tube Main Condenser/Reboiler***

In order to address the falling film (or downflow) reboiler/main condenser requirement, we performed experiments on a test section constructed with a tube bundle (19 tubes). Tests were done with water. The procedure consisted of supplying to the test section a steady flow of water. Once a steady state water level was obtained, the flowrate through each of the tubes was measured. The flow variation with respect to the average flow was calculated. Several designs were evaluated.

The design with side orifices was selected due to its superior performance, ease of manufacturing/assembly and cost effectiveness. U.S. Patent 5,699,671 assigned to Praxair shows the flow distributor with orifice design. Figure 15 shows the flow distribution with side orifices or holes. These orifices are tangentially drilled. The flow enters the tube tangentially and this aids in helping the flow adhere to the tube wall and in wetting the tube over the complete circumference of the tube. Adequate wetting of the tube surface is ensured by maintaining a minimum liquid flowrate.

## SUMMARY

The objective of the paper was to trace important developments in the falling film or downflow main condenser/reboilers.

The need for higher energy efficiency in air separation processes has been effectively addressed by the industry through significant developments in downflow main condenser/reboilers. These developments have primarily centered on two types of heat exchangers – the plate-fin brazed aluminum and the Highflux shell-and-tube type. The key areas of development are (i) the specification of minimum liquid flowrate at the exit of the reboiler vaporizing heat transfer passages and (ii) the design of flow distributors. The specification of minimum liquid flowrate is governed by the need to maintain adequate wetting of the boiling surfaces to prevent hydrocarbon accumulation and minimize fouling. The flow distributors provide uniform distribution of liquid so that minimum liquid flowrate is maintained in all the vaporizing passages. The minimum liquid flowrate depends on the type of heat exchanger, type of boiling surface, and the type of flow distributor being employed.

## NOMENCLATURE

| | |
|---|---|
| Di | tube inside diameter, m |
| g | acceleration due togravity, $ms^{-2}$ |
| $G_L$ | liquid mass flux, $kgs^{-1} m^{-2}$ |
| $G_V$ | vapor mass flux, $kgs^{-1} m^{-2}$ |
| $h_f$ | height of fin, m |
| L/V | liquid to vapor mass flowrate ratio, dimensionless |
| $\dot{M}_V$ | vapor mass flowrate, $kgs^{-1}$ |
| $N_f$ | number of fins per meter, $m^{-1}$ |
| $N_m$ | number of BAHX cores/modules |
| $N_p$ | number of vaporizing layers per BAHX core |
| $N_t$ | number of tubes per module |
| $Re_L$ | film Reynolds number, dimensionless |
| W | wetted perimeter, m |
| w | width of layer, m |
| $\Gamma_L$ | liquid flowrate per unit width ($kgs^{-1}m^{-1}$) |
| $\mu_L$ | liquid viscosity ($Nsm^{-2}$) |
| $\rho_L$ | liquid density, $kgm^{-3}$ |
| $\rho_V$ | vapor density, $kgm^{-3}$ |
| $\sigma$ | Surface tension, $Nm^{-1}$ |
| Subscript | |
| min | minimum |

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