Flow distribution, pressure drop, flooding and entrainment in an air-cooled reflux steam condenser

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Measurements on air-cooled reflux steam condensers or dephlegmators at different power plants have shown that sections of these units do not transfer heat effectively over a range of operating conditions. The ineffective areas may be due to flooding in the finned tubes although entrainment of the condensate in certain steam inlet manifolds is usually the main reason for the poor performance. Laboratory experiments were conducted to show under which conditions entrainment occurs, as well as the pressure drop and flow characteristics for different types of inlet headers or manifolds. A practical and cost effective solution is proposed to eliminate the reduction in dephlegmator performance due to entrainment in a particular manifold.

Introduction

Air-cooled steam condensers (ACCs) are finding increasing application in the cooling of power plants, not only in arid areas, but also in modern combined cycle plants where cooling tower plumes are unacceptable. An ACC may consist of a large steam supply duct which delivers steam from the turbine exhaust to a number of A-frame condenser units, as shown schematically in Figure 1.

The lower outlets of the condensers are connected to the inlet manifold of a reflux condenser or dephlegmator which results in a continuous flow of steam out of the condensers, thereby ensuring the removal of any non-condensable gases. The outlet at the top of the dephlegmator is connected to an ejector or vacuum pump. The dephlegmator finned tubes may be up to 8 m in length. Outlet air temperature measurements of some dephlegmators show that under certain operating conditions a large part of the upper section of the dephlegmator is relatively cold when compared with the steam temperature at their lower inlet. Figure 2 (right-hand of figure) shows the measured air temperature distribution at the outlet of a dephlegmator.

Under certain conditions of reflux steam condensation in long inclined tubes, flooding may occur, resulting in an accumulation of condensate in the tubes. It was previously thought that this was the probable reason for the reduction in performance. Recent reliable equations that predict the "onset" of flooding, however, suggest that this is rarely the case in most practical dephlegmators.[1,2,3]

The accumulation of condensate inside the dephlegmator tubes is however often due to entrainment of condensate in the dephlegmator inlet manifold. The performance characteristics of two different types of manifolds or headers were investigated experimentally.

Apparatus

D-type inlet manifold

An example of a practical D-type manifold as shown in Figure 3 finds application in many air-cooled steam reflux condensers that make up a part of an ACC system.

A practical full-scale model of a dephlegmator incorporating a D-type manifold as shown in Figure 4 was constructed for testing in the laboratory.

The dephlegmator bundle consists of two rows of 1600 mm long finned tubes connected to a Perspex (to make visual observation possible) D-type inlet manifold at the lower end. The manifold is connected to a 700 mm diameter Perspex header pipe via 178 mm diameter Perspex stubs. Measured quantities of air are supplied to the dephlegmator tubes via this header pipe. The condensate in the individual tubes is simulated by introducing a prescribed flow of water via plastic tubes from a constant head tank located above the tube bundle. Pressure differences are measured between the D-type manifold p_2 and the ambient pressure p_3, i.e. $\Delta p_{23} = p_2 - p_3$.

Box-type inlet manifold

A schematic drawing of a box-type inlet manifold or header located at the lower inlet end of a dephlegmator unit (consisting of four heat exchanger bundles on either side of an A-frame) is shown in Figure 5. Excess steam from the condensers enters the header pipe from both sides.

A partial full-scale model of a dephlegmator incorporating a box-type header was constructed for testing in the laboratory. The "dephlegmator" bundle consists of two rows of 2000 mm long finned tubes connected to a Perspex box-type manifold at the lower end. Measured quantities of air are supplied to the dephlegmator tubes via this header pipe. The condensate in the individual tubes is simulated by introducing a prescribed flow of water via plastic tubes from a constant head tank located above the tube bundle. Pressure differences are measured between a point located near the inlet of each tube (200 mm from the lower inlet) and the ambient pressure p_3, i.e. $\Delta p_{23} = (p_2 - p_3)$.

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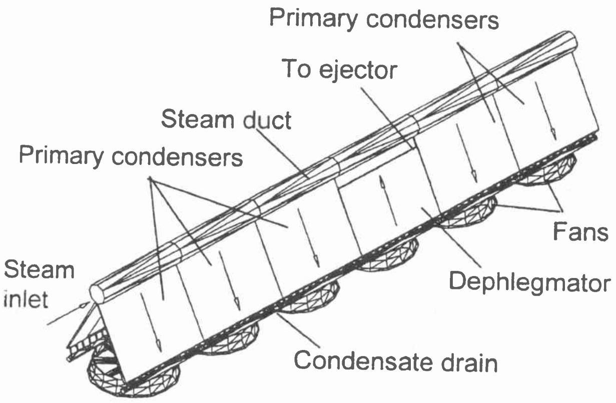

Figure 1 Air-cooled steam condenser

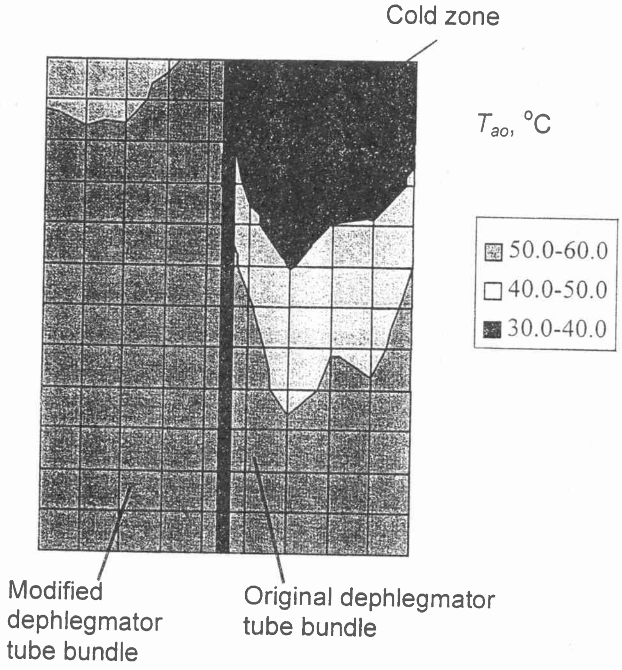

Figure 2 Temperature distribution in dephlegmator

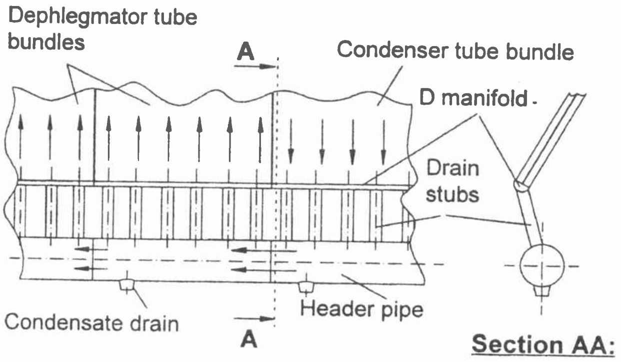

Figure 3 D-type inlet manifold

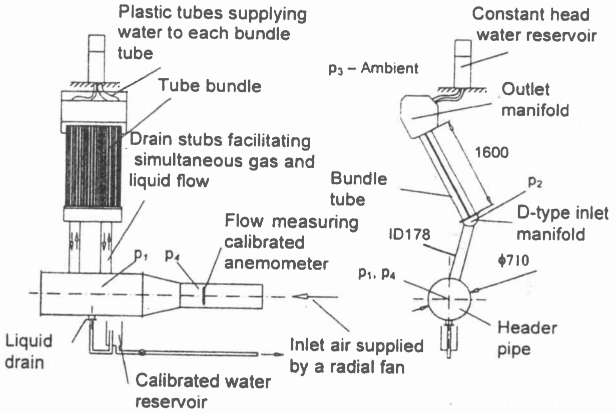

Figure 4 Model dephlegmator

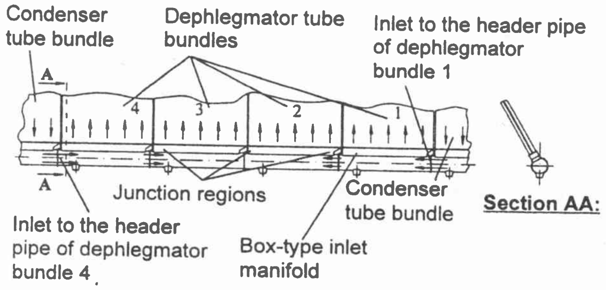

Figure 5 Box-type inlet manifold

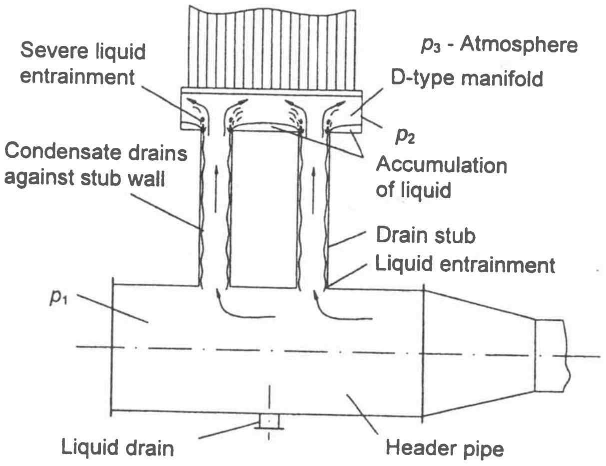

Figure 6 Flow patterns in D-type manifold

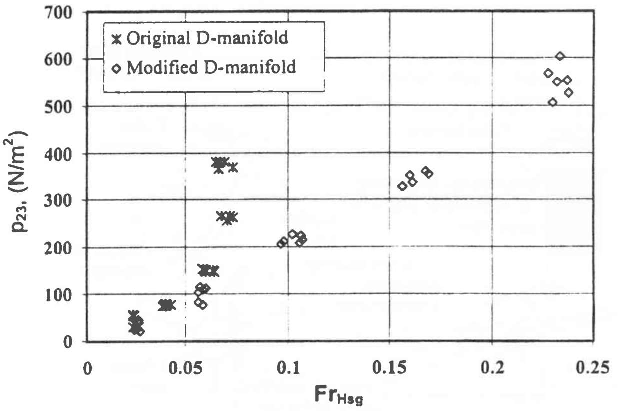

Figure 7 Pressure difference

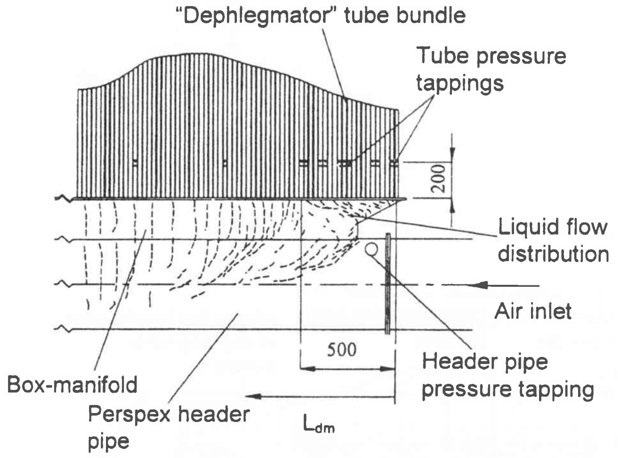

Figure 8 Droplet trajectories in manifold

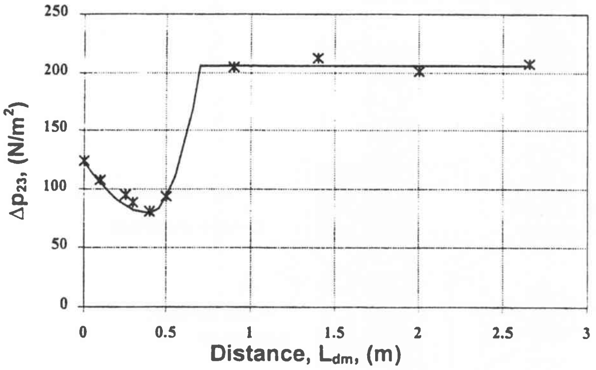

Figure 9 Pressure difference at different downstream manifold locations

To ensure that airflow patterns at the inlet to the header pipe are realistic, a partial condenser model, with concurrent air and water downflow is located upstream of the dephlegmator.

Results

D-type heater inlet manifold

Figure 6 is a schematic of the visible flow patterns in the manifold at the inlet to the dephlegmator. Severe entrainment of the water entering the top of the stubs occurs even at relatively low air flow rates. A part of the entrained liquid enters the tubes whilst a significant amount of liquid is retained in the D-type manifold.

According to predictions[1,2,3] the particular dephlegmator tube should flood at a densimetric gas Froude number in the range $0.4 < \mathrm{Fr}_{Hsg} < 0.5$. As shown in Figure 7 present tests show that a significant increase in pressure drop Δp_{23} already occurs at a densimetric Froude number as low as 0.07. Dephlegmator performance will therefore already decrease at this low value.

To improve the performance of existing dephlegmators incorporating D-type headers, the latter can be modified by draining condensate through downpipes located between the steam vapour supply stubs. Entrainment is thereby essentially eliminated and a gradual increase in pressure drop is experienced as is shown in Figure 7.

The proposed modification was implemented in the dephlegmator of a large power plant ACC. As shown in Figure 2 the performance of the modified half of the dephlegmator bundle is greatly improved when compared to the original bundle.

Box-type inlet manifold

The droplet trajectories in the experimental box-type manifold are shown schematically in Figure 8. Due to separation of the air flow at the inlet to the manifold, recirculation occurs in this region.

The pressure difference Δp_{23} measured between a location 200 mm from the lower inlet to the tubes and the ambient pressure is shown in Figure 9 for different positions of the "dephlegmator" downstream from the manifold inlet flange.

The pressure differential is clearly smaller near the inlet where flow separation occurs. Due to the lower pressure drop in the upstream dephlegmator tubes less air will tend to flow through them when compared to tubes further downstream. In a practical dephlegmator this may lead to backflow of steam into the upper open ends of the upstream tubes. To avoid an accumulation of noncondensables in these tubes an ejector of sufficient capacity is required at the upper end of the dephlegmator.

Conclusion

Many dephlegmators or reflux condensers at power plants, incorporating direct air-cooled steam condensers, experience condensate entrainment at their lower steam inlet headers (D-type) resulting in measurable reductions in performance. By modifying existing headers or installing box-type headers in new plants, this problem can be essentially eliminated.

References

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