Flow loss coefficients at air-cooled condenser finned tube inlets

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In a typical air-cooled steam condenser of a power generating plant, the turbine exhaust steam flows via a distribution pipe or dividing header into numerous finned tubes or laterals. The steam flow distribution in air-cooled condensers must be quantified to assure a sufficiently high steam flow rate into every lateral to avoid the accumulation of non-condensable gases in the lower section of any lateral. The flow through a lateral is, amongst others, a function of the flow resistance at the lateral inlet which can be expressed in terms of a loss coefficient. The magnitude of the lateral inlet loss coefficient as found in a typical air-cooled condenser is investigated experimentally. It is found that the inlet loss coefficients of the individual laterals vary, with the first lateral (upstream lateral) experiencing the greatest value. Furthermore it is observed that the inlet loss coefficients are a function of the dividing header flow velocity. A reduction in inlet loss coefficient can be obtained by placing a backward facing step or a small wedge-like ramp upstream of the first lateral or by installing a suitable grid near the lateral inlets.

Nomenclature

f_D	Darcy friction factor	
K	Loss coefficient	
L	Length	m
p	Pressure	N/m^2
v	Velocity	m/s
α_e	Energy correction coefficient	
ρ	Density	kg/m^3

Subscripts

e	Equivalent
h	Header
i	Inlet
l	Lateral
vr	Velocity ratio

Introduction

A typical air-cooled steam condenser is shown in Figure 1. Steam enters the finned tubes or laterals from a pipe or dividing header. The flow situation found in the dividing header of an air-cooled condenser is simulated experimentally in a test section as shown diagrammatically in Figure 2. Equally spaced laterals suck off flow from the dividing header. As the nett dividing header flow is perpendicular to the laterals, flow separation from the edges of the lateral inlets occurs because of inertia forces. The entering flow forms a vena contracta and during the re-expansion, irreversible conversions or losses in mechanical energy occur.

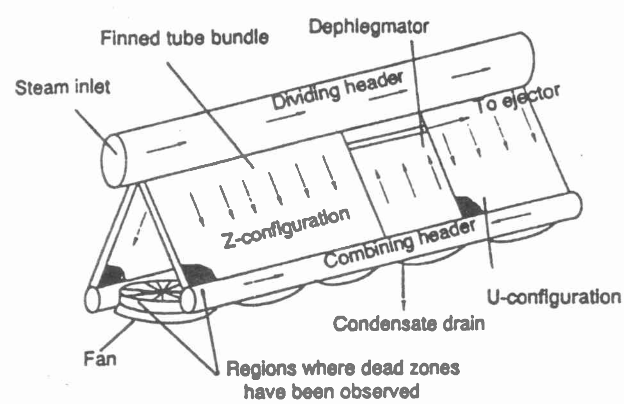

Figure 1 Diagram of an air-cooled condenser

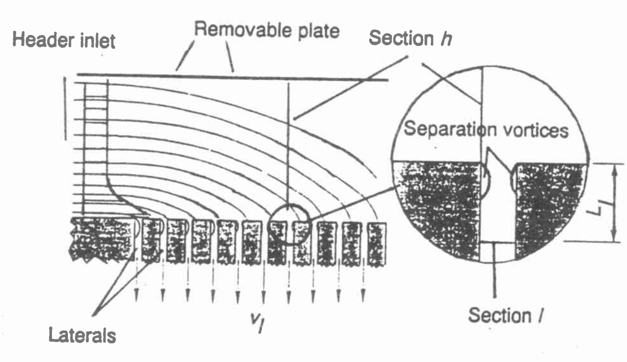

Figure 2 Lateral inlet configuration in experimental apparatus

Definition of the Inlet Loss Coefficient

Referring to Figure 2, the energy equation is applied to the flow between section h in the header and a section l in a lateral at a distance L_l downstream of its inlet where the flow is fully developed and the inlet loss coefiicient is defined by the following equation:

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$$\left(K_i + f_D \frac{L_l}{d_{el}}\right)\frac{v_l^2}{2} = \left(\frac{p_h}{\rho} + \alpha_{eh}\frac{v_h^2}{2}\right) - \left(\frac{p_l}{\rho} + \frac{v_l^2}{2}\right) \quad (1)$$

or

$$K_i = \frac{p_h - p_l}{\frac{1}{2}\rho v_l^2} + \alpha_{eh}\frac{v_h^2}{v_l^2} - 1 - f_D \frac{L_l}{d_{el}} \quad (2)$$

where α_{eh} is the energy correction factor in the header. It is assumed that the velocity distribution is uniform at L_l and the flow is incompressible.

The Darcy friction factor for turbulent flow in a high aspect ratio flattened finned tube (modern air-cooled single-row-condenser tube) may be approximated by the following equation which is applicable to flow between parallel plates:[1]

$$f_D \left(2\log_{10}\left(Re_l f_D^{0.5}\right) - 1.19\right)^{-2} \quad (3)$$

where Re_l is based on the hydraulic diameter of the flattened finned tube (d_{el}).

In view of the fact that α_{eh} is usually not known, it is convenient to define the following loss coefficient:

$$K_i' = K_i - \alpha_{eh}\frac{v_h^2}{v_l^2} = \frac{p_h - p_l}{\frac{1}{2}\rho v_l^2} - 1 - f_D \frac{L_l}{d_{el}} \quad (4)$$

This inlet loss coefficient can be determined from experimental data without having to consider the velocity profile in the dividing header.

In order to make allowance for machining inaccuracies that occur during the manufacturing of the laterals of the experimental apparatus, the inlet loss coefficients of the individual laterals are compared by making use of a reference inlet loss coefficient which is subtracted from K_i'. The normal inlet loss coefficient, K_0, is defined as the inlet loss coefficient of a single lateral into which flow is sucked from an infinite still reservoir.

Experimental Apparatus

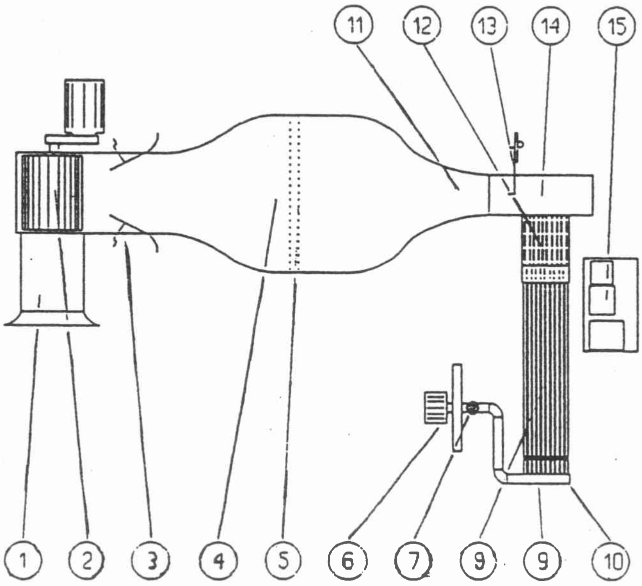
A plan view of the experimental apparatus is shown diagrammatically in Figure 3. The main part of the apparatus, the lateral inlet box which is attached to the outlet of a wind tunnel, consists of up to 10 equally spaced laterals to simulate the flattened finned tube inlets of an air-cooled condenser. Referring to the assembly drawing shown in Figure 4, the laterals which have sharp edged inlets, are 10mm wide, 190mm high and 400mm long and are spaced at a pitch of 40mm. The wind tunnel outlet represents a dividing header to which the lateral inlet box is fitted in such a way that the laterals branch off perpendicularly to the nett header flow direction. Air is sucked into the laterals by a centrifugal fan. The fan is connected to a suction manifold which collects the flow from the aluminium pipes being individually connected to the lateral outlets. These pipes are used to determine the mass flow rate through each lateral and thereby its air velocity. Each pipe has two pressure tappings situated 1m apart over which the pressure loss due to pipe friction is measured and converted to a mass flow rate via a calibration equation. The header velocity is determined by means of a pitot static tube facing into the wind tunnel outlet, positioned 100mm upstream of the first lateral and in the centre of the header cross-sectional flow area. Every lateral has two pairs of pressure tappings facing each other on the top and bottom plates of the lateral inlet box, situated at a distance of 200mm and 350mm from the lateral inlets. The differences in the pressure measured at these tappings and the header pressure are used to determine the lateral inlet loss coefficient. The header can be configured in two different ways as shown in Figures 5 and 6, respectively: two-dimensionally where the header, 330mm wide and 190mm high, connects smoothly to the lateral ends, and three-dimensionally where the header, 330mm wide and 660mm high, allows the flow to enter the laterals from the lateral ends as well. In an air-cooled condenser often one or a combination of these two configurations is found. In the two-dimensional configuration the plane of the header opposite the lateral inlets can be left open or it can be closed with a plate with ten pressure tappings situated opposite the laterals. The open configuration ensures an approximately constant atmospheric header pressure. An unquantifiable amount of ambient air, however, is also sucked through the open plane to possibly influence the magnitude of the lateral inlet loss coefficients. The plate with the pressure tappings was used to investigate the validity of the experimental results obtained with the open header configuration and good agreement was achieved.

Experimental Results

During all experiments mean lateral velocities were kept uniform and constant at approximately 11 m/s. The normal inlet loss coefficients (K_0) of the individual laterals having sharp edged (90°) inlets, were determined by closing the remaining nine laterals with masking tape to achieve a flow contraction area ratio of practically zero and with a zero header velocity. Due to inaccuracies that had occurred during manufacturing of the apparatus, differences were found in the individual values. The average value was found to be 0.448 while the maximum deviation was in the order of 8%.

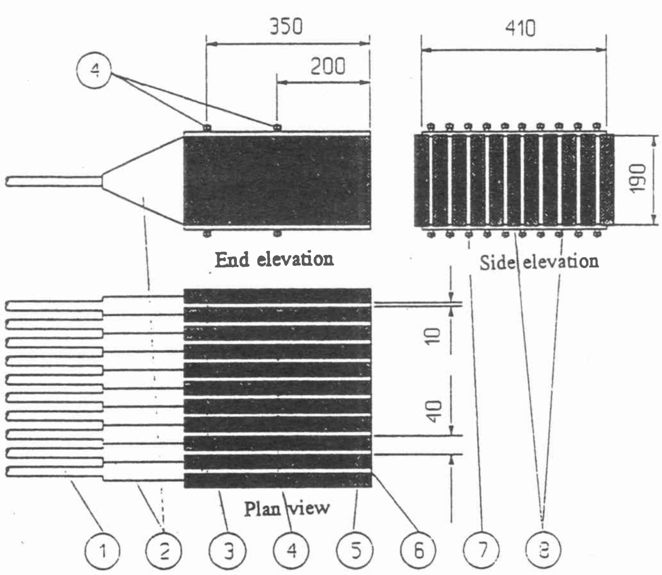
The first experiment involved a single lateral with a passing header flow of varying velocity in a two-dimensional configuration. The K_{ivr} value of a single lateral as a function of the header inlet velocity to lateral velocity ratio, or in short, the velocity ratio is shown in Figure 7. The K_{ivr} value increases almost linearly with increasing header velocity. The data agree well with that of Nosova[2] and Van Heerden[3] who, respectively, used laterals of 40mm width and 400mm height, and of 16mm width and 182mm height.

The K_{ivr} values of ten consecutive laterals are shown in Figure 8 as a function of the velocity ratio for the two-



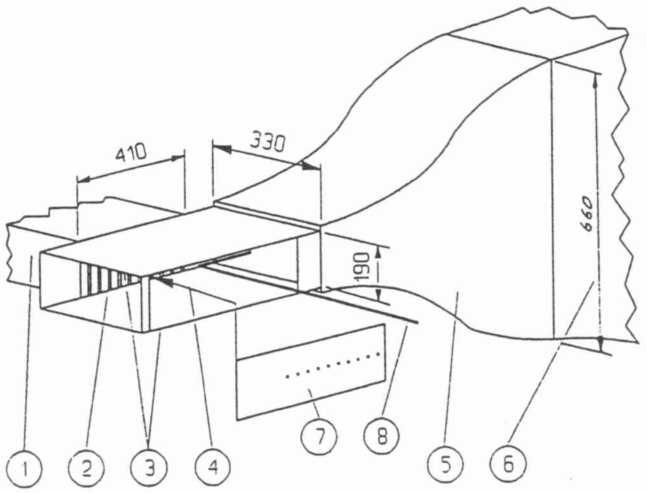
Legend: 1) Wind tunnel fan inlet; 2) Wind tunnel fan (centrifugal); 3) Flow adjustment flaps; 4) Expansion chamber; 5) Screen; 6) Suction fan (centrifugal); 7) Suction fan flow adjustment valve; 8) Aluminium pipes for flow measurement; 9) Suction manifold; 10) Pipe flow adjustment valves; 11) Wind tunnel converging section; 12) Lateral inlet box; 13) Pitot static tube; 14) Header; 15) Data acquisition system.

Figure 3 Plan view of entire apparatus



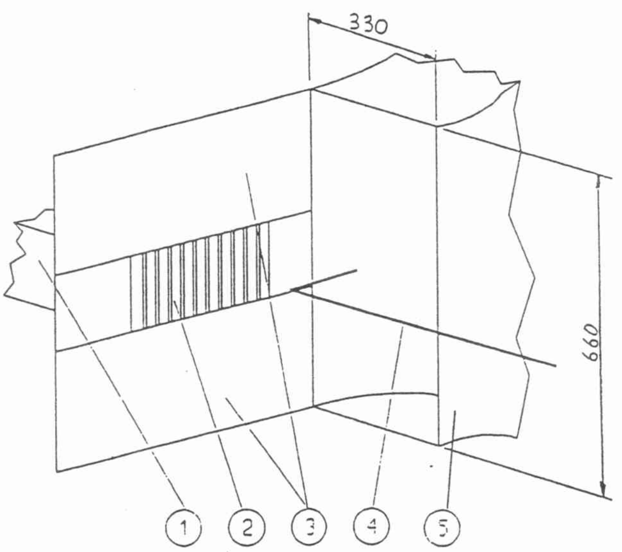
Legend: 1) Calibrated aluminium pipe (for flow measurement); 2) Lateral outlet manifold connecting each individual lateral leading to calibrated aluminium pipes; 3) PVC blocks; 4) Pressure tappings in top and bottom aluminium plates; 5) Lateral; 6) Lateral inlet face; 7) Pressure tapping fitting; 8) Top and bottom aluminium plates with 30mm×3mm grooves at 40mm pitch.

Figure 4 Assembly drawing of lateral inlet box with connecting manifold



Legend: 1) Lateral inlet box; 2) Lateral inlets; 3) Top and bottom plates; 4) Header; 5) Detachable converging section; 6) Fixed wind tunnel outlet section; 7) Wall for closed configuration; 8) Pitot static tube.

Figure 5 Lateral inlet box attached to wind tunnel outlet in two-dimensional configuration indicating the difference between open and closed header



Legend: 1) Lateral inlet box; 2) Lateral inlets; 3) Extension plates of wind tunnel outlet; 4) Pitot static tube; 5) Fixed wind tunnel outlet section.

Figure 6 Lateral inlet box attached to wind tunnel outlet in open three-dimensional configuration

dimensional configuration. The K_{ivr} value of a single lateral as a function of the header inlet velocity to lateral velocity ratio, or in short, the velocity ratio is shown in Figure 7. The K_{ivr} value increases almost linearly with increasing header velocity. The data agree well with that of Nosova[2] and Van Heerden[3] who, respectively, used laterals of 40mm width and 400mm height, and of 16mm width and 182mm height.

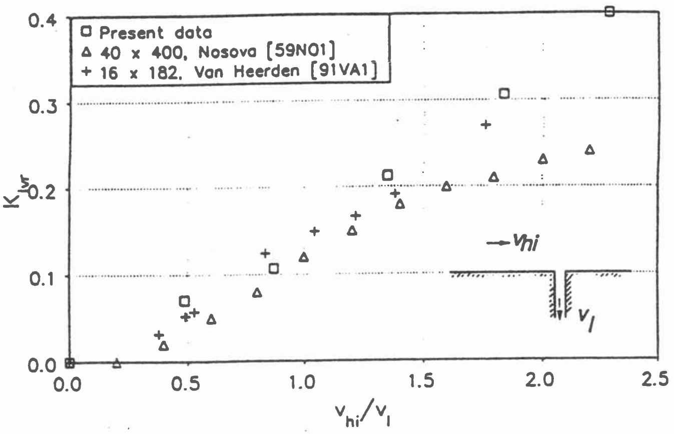


Figure 7 K_{ivr} values of a single lateral with sharp inlet in passing flow, two-dimensional configuration

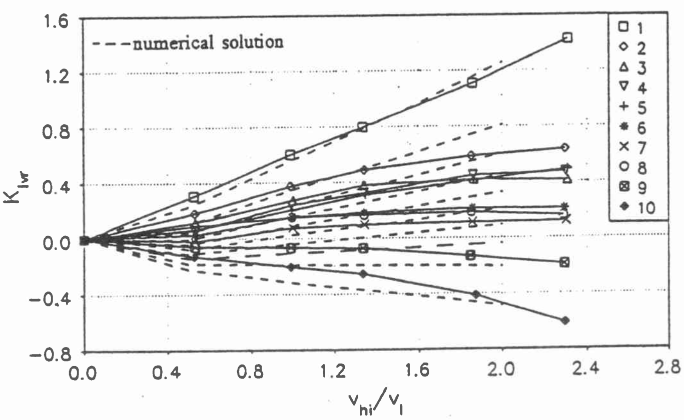


Figure 8 K_{ivr} values of 10 laterals in two-dimensional standard configuration compared to numerical solution

The K_{ivr} values of ten consecutive laterals are shown in Figure 8 as a function of the velocity ratio for the two-dimensional configuration. This configuration is called the standard configuration to be referred to in comparisons to other geometric configurations. It can be seen that the K_{ivr} value of the first upstream lateral increases more significantly as a function of increasing velocity ratio than those of the remaining laterals. The last two laterals (No. 9 and No. 10) experience a decrease in their K_{ivr} value with increasing velocity ratio. A numerical investigation of this flow situation was performed with the PHOENICS computer code. The K_{ivr} values determined from the solution of the code agree well with those determined experimentally as can be seen in Figure 8. The decrease in the K_{ivr} values of the last two laterals is also obtained with the numerical investigation.

For the three-dimensional configuration as in the experimental arrangement shown in Figure 6, the K_{ivr} values of the laterals are shown in Figure 9, in which the K_{ivr} values of the first lateral of the standard configuration are also presented. It can be seen that the K_{ivr} value of the first lateral of the three-dimensional configuration is lower than that in the case of the standard configuration, while that of the last lateral (No. 10) is almost the same as in the two-dimensional configuration.

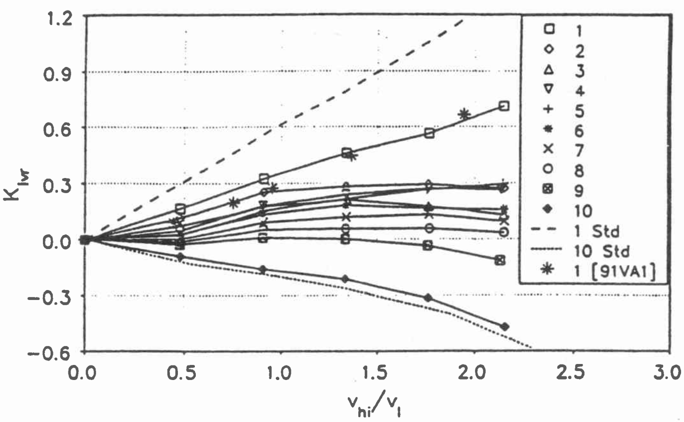


Figure 9 K_{ivr} values of 10 laterals in three-dimensional standard configuration

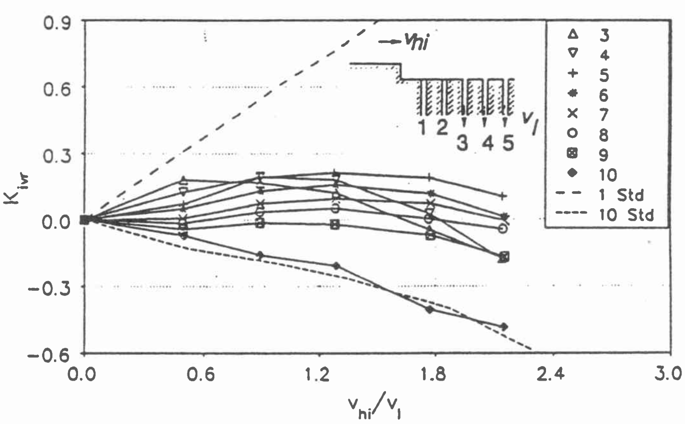


Figure 10 K_{ivr} values of 8 laterals in two-dimensional configuration with backward a 20mm facing step 100mm upstream of first lateral

A backward facing 20mm step situated 100mm upstream of the first lateral of 8 (the first two laterals, No. 1 and No. 2, were closed to create the upstream distance) in the open two-dimensional configuration reduces the K_{ivr} value of this first lateral significantly compared to the first lateral of the standard configuration. The reason for this step is to facilitate the flow into the first upstream lateral by generating a separation vortex. The experimental results are shown in Figure 10. Similarly a wedge, 10mm high and 20mm long, situated 80mm upstream of the first lateral decreases the K_{ivr} value of the first upstream lateral. The experimental results are shown in Figure 11. The data of both configurations are compared to the K_{ivr} values of the first and the last lateral of the standard configuration.

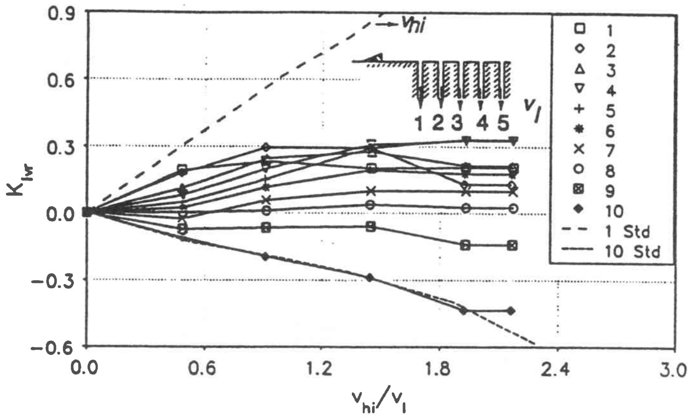


Figure 11 K_{ivr} values of 10 laterals in two-dimensional configuration with wedge 80mm upstream of first lateral

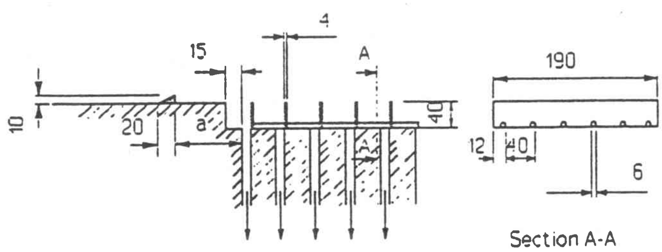


Figure 12 Lateral inlets with grid configuration

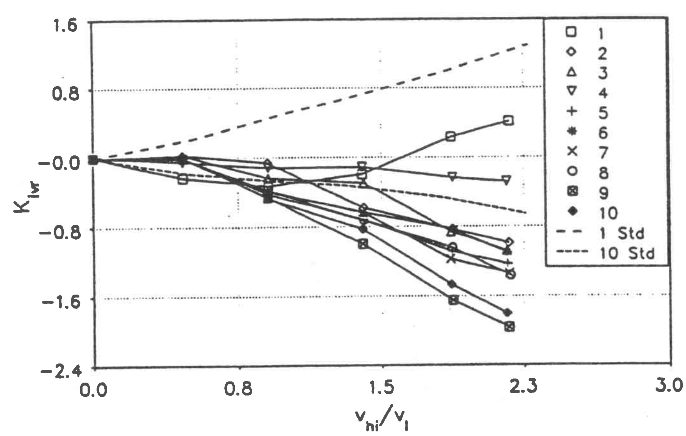


Figure 13 K_{ivr} values of 10 laterals with grid and wedge 80mm upstream of the first lateral

A grid used for industrial walk-ways is fitted to the lateral inlets as shown in Figure 12. The function of the grid is to prevent high velocity saturated water droplets from causing erosion at the lateral inlets in the condensers. The K_{ivr} values of the laterals with the grid configuration and an upstream wedge is shown in Figure 13. Again a reduction in the K_{ivr} values is obtained.

In a practical air-cooled condenser the finned tubes are welded to the header wall. The welding seam forms a rounded inlet. In order to investigate the effect of this rounding, the inlet edges at the lateral inlet are rounded with a radius of 3mm to resemble the welding seam. The normal inlet loss coefficients of the rounded inlets are determined.

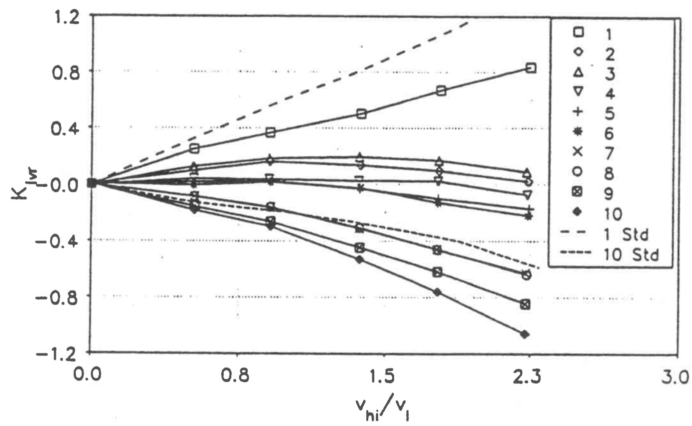


Figure 14 K_{ivr} values of 10 laterals with rounded inlet edges in two-dimensional configuration

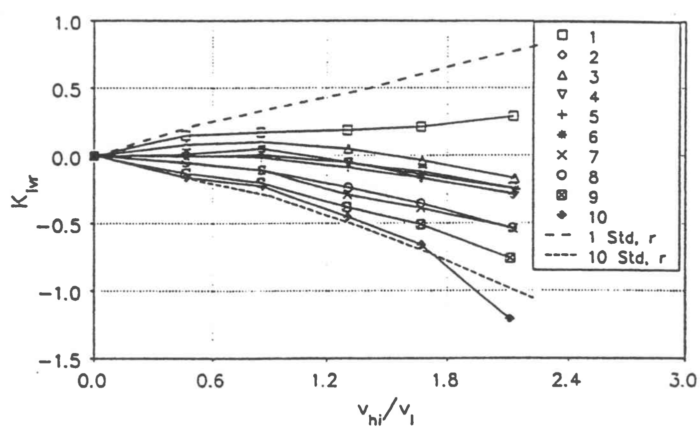


Figure 15 Reduced inlet loss coefficient of 10 laterals with rounded inlet edges in three-dimensional configuration

The average K_{0r} value is 0.089 which is significantly lower than that of the sharp inlet configuration. Again differences of the values of the individual laterals are observed, which are found to deviate up to 50% from the average value due to the small measured pressure differences. This large deviation results from the small pressure change over the lateral inlets. The K_{ivr} values for the two-and three-dimensional header configurations are shown in Figures 14 and 15, respectively. The K_{ivr} values are found to be lower than those of the standard configuration. A similar trend of the K_{ivr} values is observed as in the case of the sharp inlet configuration.

Discussion and Conclusion

The reason for the first (upstream) lateral experiencing a relatively high inlet loss coefficient is primarily due to the high local header velocity perpendicular to the lateral inlet caused by the suction of the downstream laterals. In the three-dimensional configuration this effect is shown to be smaller since air is supplied to the laterals situated downstream of the first lateral from the lateral sides and therefore the velocity component in the free stream direction is smaller, hence the smaller inlet loss coefficient. The rounded inlets have significantly smaller inlet loss coefficients than those with sharp edges.

The inlet loss coefficients presented in this paper can be used in the modelling of the steam flow through an air-cooled condenser.

The high inlet loss coefficient experienced by the first lateral in some of the investigated cases can contribute to the formation of dead zones in the first upstream finned tubes as observed in existing air-cooled condensers since the mass flow rate into this tube is usually significantly more impeded than that into the other tubes. The geometries of the step, the wedge, and the grid can be applied to facilitate the flow into these laterals.

References

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