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Heat transfer of a U-bend in a cross flow of air at different angles of incidence

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Abstract

An experimental investigation into the incidence angle dependence on mean external heat transfer coefficient for a circular U-bend (180°) in a cross flow of air was performed. All tests were performed on a U-bend with a curvature ratio (δ) of 0.296 covering a Reynolds number range of 1.2×10^4 to 2.7×10^4, while imposing a uniform wall temperature boundary condition. It was found that the U-bend had maximum external heat transfer rate when the external air flow velocity vector was nearly parallel to the bend plane (angle-of-incidence equals 0°). As the angle-of-incidence increased, the external heat transfer coefficient for the U-bend decreased. As the angle-of-incidence approached 90°, the external heat transfer coefficient for the U-bend asymtoped to the value for corresponding flow over a circular cylinder of the same outer diameter.

1. Introduction

U-bends are commonly found in serpentine heat exchangers, which are used in heating systems such as residential gas furnaces. A typical serpentine passage will contain three–five bends which can account for up to 20% of the total running length of a serpentine passage. Therefore, optimal orientation of the bend surfaces to the direction of the circulating air flow is one way to increase the efficiency of the serpentine heat exchangers.

Fig. 1 shows one possible orientation of a U-bend in a uniform external flow field. The U-bend connects two parallel straight pipe sections, The axes (C1 and C2) of the parallel straight pipes are in the same plane, so is the curved axis of the bend interior (Cb). This plane can be defined as the bend plane. The external flow is usually designed to be perpendicular to the straight pipe sections. In Fig. 1, the external flow velocity vector is parallel to the bend plane.

The angle-of-incidence of external flow can be defined as the angle between external flow velocity vector and the bend plane. Therefore, in Fig. 1, the angle-of-incidence is 0°. An angle-of-incidence of 30° can be achieved by rotating the bend plane 30° clockwise (or counter-clockwise) with respect to centerline of the system, *N–N*, without changing the external flow field in the meantime, see Fig. 1. Similarly, any angle-of-incidence between 0 and 90° can be achieved by simply rotating the bend plane with respect to centerline *N–N*. The heat transfer characteristics of a U-bend under different angles-of-incidence would be of interest to design engineers seeking the optimal orientation of the U-bend in cross flow.

A search in the open literature for the external fluid flow and heat transfer around a U-bend found one recent investigation. Harris and Goldschmidt [1]

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Nomenclature

a	outer pipe radius
c_p	constant-pressure specific heat
d	outer pipe diameter, $2a$
h	convection heat transfer coefficient
j_{fg}	enthalpy of evaporation
k	fluid thermal conductivity
L	separation distance, or length
m	meters
$\dot{m}$	mass flow rate
Nu	Nusselt number (hd/k)
R	radius of bend curvature
Re	Reynolds number (Ud/ν)
s	seconds
T	temperature
U	fluid velocity
x	distance

Greek symbols

δ	curvature ratio (ratio of pipe radius to bend radius, a/R)
ν	kinematic viscosity
Θ	angle-of-incidence (degree)

Subscripts

air	air
bend	U-bend section
straight	straight pipe section
d	diameter
steam	steam
amb	ambient or free stream

did an experimental investigation of the external heat transfer of a U-Bend in cross flow specifically studying the influence of curvature ratio on heat transfer. They covered a Reynolds number range of 3000 to 80,000 while imposing a uniform wall temperature (UWT) boundary condition. The measurements were acquired for 0° angle-of-incidence condition where the external flow velocity vector was parallel to the bend plane. One data set reported angle-of-incidence measurements for 0, 45, and 90°. The results showed that the bend had the maximum heat transfer at 0°. However, no angle-of-incidence trends were established. No investigation has been published reporting the dependence of external heat transfer of a U-bend on different angle-of-incidence and Reynolds numbers. Representable results will now be presented.

The external heat transfer of a U-bend is closely related to a system of two circular cylinders in cross flow, since the bend geometry can be regarded loosely as two quasi-straight pipe sections connected by a spherical cap [2]. The two quasi-straight pipe sections can be modeled as a system of two circular cylinders separated by a certain distance, depending on the cur-

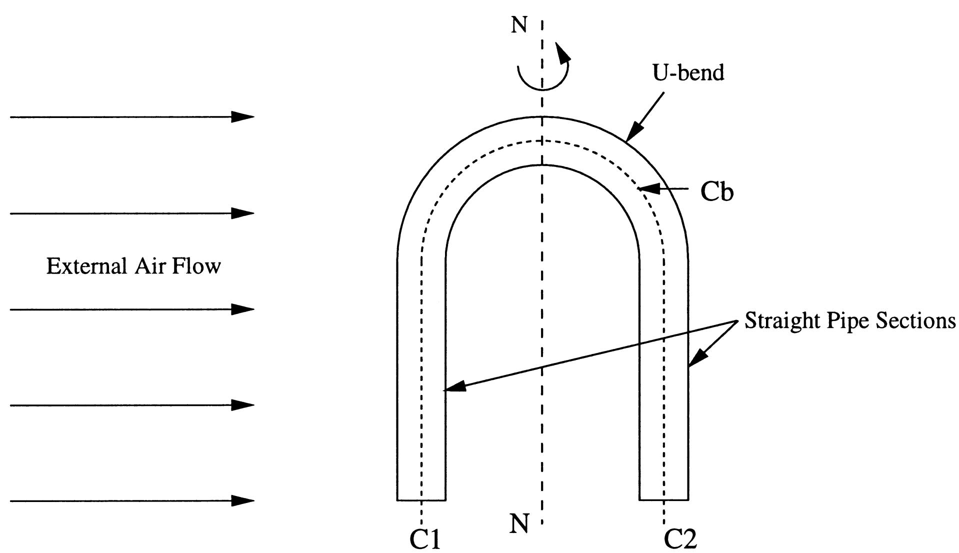

Fig. 1. A U-bend in cross flow (0° angle-of-incidence shown).

vature of the bend. Therefore, information about a system of two circular cylinders in cross flow might give some useful insight about the behavior of a U-bend under the same external flow conditions.

Published data on the flow around two circular cylinders are also limited. The most recent experimental investigation of the flow around two circular cylinders arranged in tandem was performed by Igarashi [3]. It was found that quasi-stationary vortices were formed between cylinders up to $L/d = 3.5$ when the Reynolds number was varied in the range of subcritical values (8.7×10^3–5.2×10^4). He also recognized a dependency of flow structure on Reynolds number in the range $1.1 \leq L/d \leq 2.0$.

The heat transfer characteristics of two circular cylinders in cross flow arranged in tandem were studied by several investigators [4–6]. Kostić and Oka did extensive local and mean heat transfer measurement of two circular cylinders in cross flow [4]. They discovered that the wake effect of the first cylinder would enhance the heat transfer of the downstream cylinder so that the mean heat transfer coefficient of the system would be greater than that of a single cylinder in cross flow. The enhancement effect was also observed by Aiba [6].

The angle-of-incidence of the external flow was found to have important effects on the heat transfer of a system of two circular cylinders. Daujotas et al. reported experimental results of a system of two circular cylinders differently oriented in cross flow [5]. They discovered that the enhancement of heat transfer was maximum when cylinders were arranged in tandem. As the angle-of-incidence of the external flow increased, the enhancement decreased.

To find out if the trends for systems of two circular cylinders reported by Daujotas et al. [5] could be applied to U-bends, an experimental investigation was deemed necessary to determine the heat transfer characteristics of a U-bend differently oriented in cross flow. Therefore, using the same experimental methodology as Harris [2], experiments were carried out to study the heat transfer of a U-bend in cross flow, at differing angles-of-incidence.

2. Test procedure

The experimental setup was discussed by Harris and Goldschmidt [1] and is briefly reviewed here. A U-bend section ($\delta = 0.292$) was subject to an external uniform air stream with 0.1% free stream turbulence provided by the Herrick Labs wind tunnel. The wind tunnel test section is 60 cm ($23\frac{3}{4}$ in.) high by 45 cm

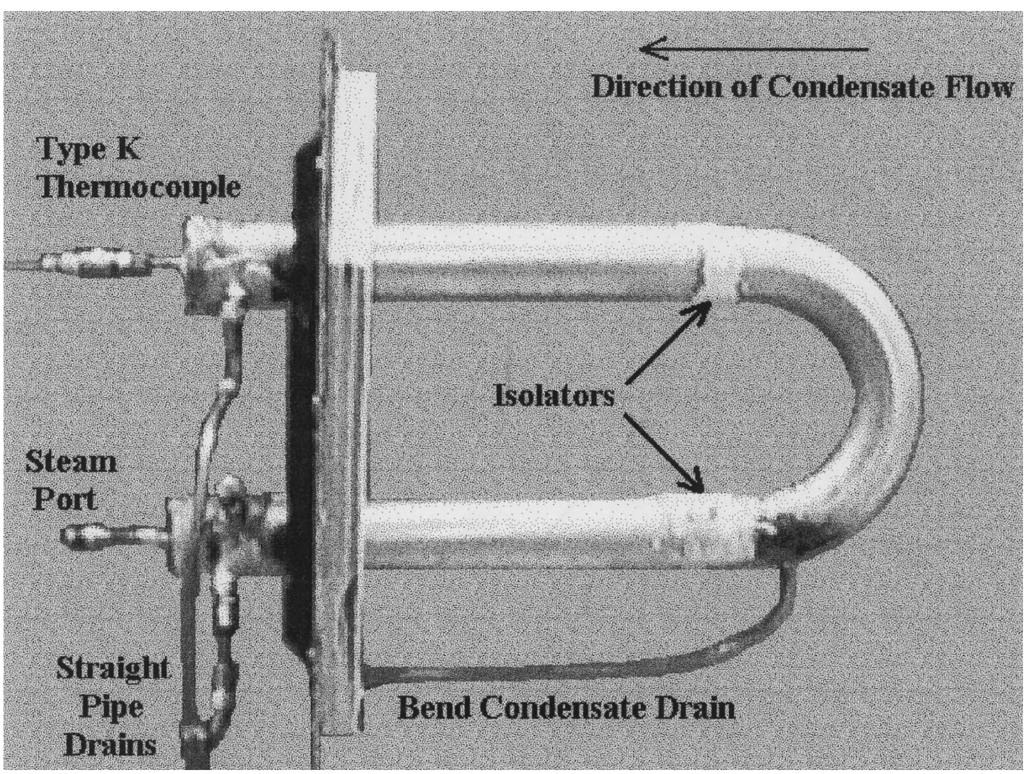

Fig. 2. U-bend test specimen at 90° orientation (external flow is normal to the paper).

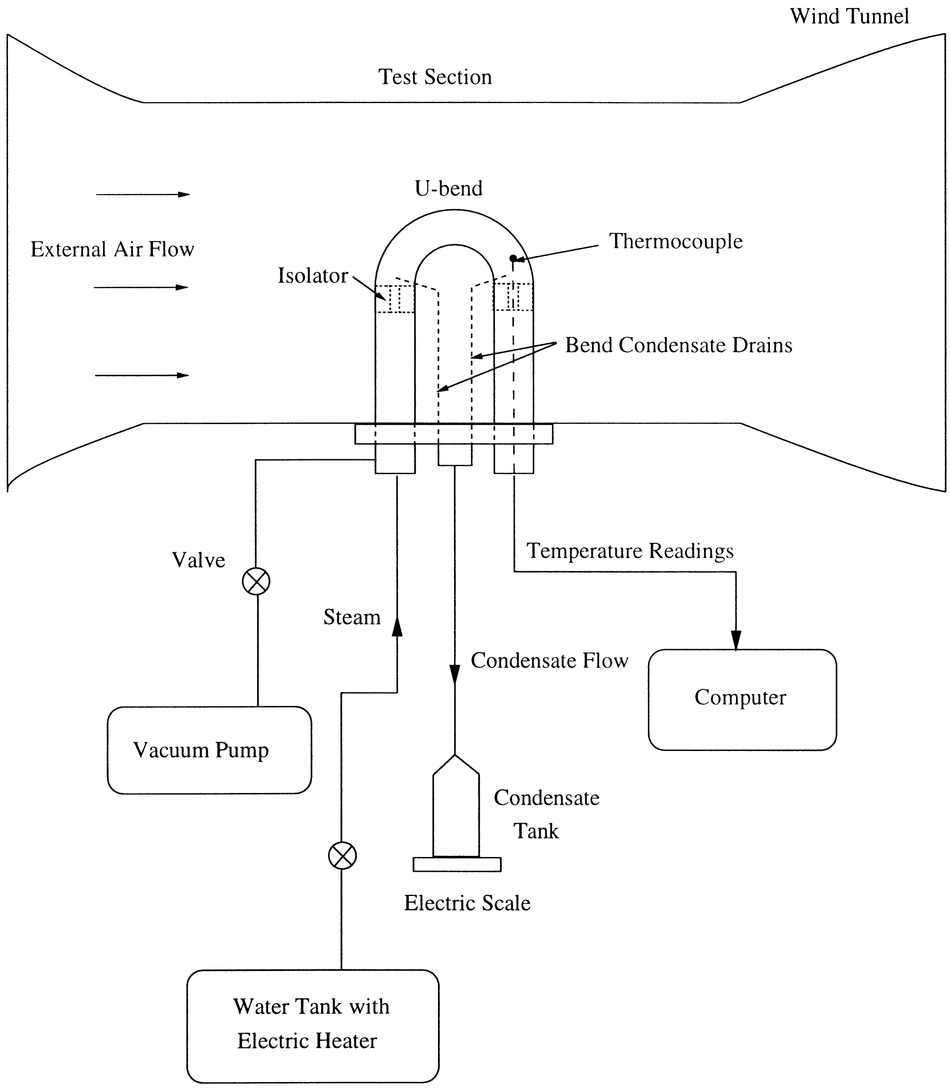

Fig. 3. U-bend experimental set-up.

($17\frac{3}{4}$ in.) wide by 154 cm ($60\frac{1}{2}$ in.) long [2]. The external flow velocity was measured with a pitot tube.

The heat transfer through the entire bend section was found by measuring the condensation rate of saturated steam on the inner surface of the U-bend for a given flow rate of air across the outer surface. The U-bend section used for testing contained adjoining straight pipe sections needed for structural support. The bend was fabricated with 4.45 cm (1.75 in.) outer diameter aluminized steel with a bend radius of 7.62 cm (3 in.), $\delta = 0.292$. The curved section of the U-bend was physically separated with fiberglass isolators from the two 17.8 cm (7 in.) long straight pipe sections. These isolators separate the condensate in the curved section from the condensate in the two straight pipe sections adjoining the bend. The condensates from the curved and straight pipe sections were collected separately. The steam temperature was measured by a 45.7 cm (18 in.) long Type K thermocouple which was inserted into the inner volume of the curved section. A photograph of the test section for 90° angle-of-incidence configuration is shown in Fig. 2. The same test specimen was also modified to measure incident angles of 0–45°. This was accomplished by turning the U-bend and relocate the drain (which collected the condensate due to gravity forces).

Schematic of the experimental arrangement is shown in Fig. 3. The test procedure was as follows. The inner bend volume was first evacuated and then filled with saturated (pure) steam. The inner

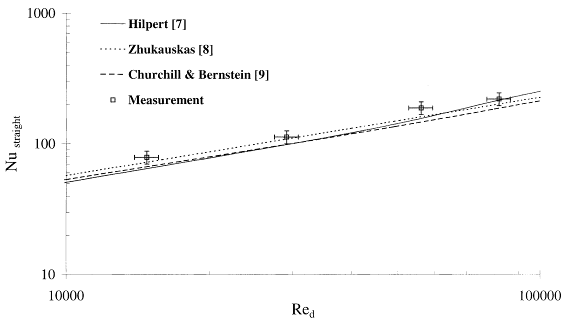

Fig. 4. Comparison of measurements to correlations for heat transfer of a heated cylinder in cross flow.

volume, and hence the inner surface was then held at the saturation temperature as external air stream flowed across the outer surface. After steady-state conditions were reached, the condensate was collected over a 10-min interval and mass measured directly using a scale sensitive to 0.01 g. The internal steam temperature was measured and enthalpy of evaporation determined from steam tables. As the conduction resistance of the wall was found to be negligible compared to convection resistance, the external Nusselt number was found by reducing the data as shown in Eq. (1).

$$Nu = \frac{\dot{m} \cdot j_{fg}}{k_{\text{air}} \cdot \pi^2 \cdot R \cdot (T_{\text{steam}} - T_{\text{amb}})} \quad (1)$$

The experimental methodology was previously verified by measuring the heat transfer from steam heated straight pipe sections in cross flow using the test specimen of Fig. 2. Results were then compared to familiar engineering correlations in literature for a cylinder in cross flow including Hilpert [7], Žhukauskas [8], and Churchill and Bernstein [9]. The results were reported by Harris and Goldschmidt [1], Fig. 4. A statistical fit of the measurements produced Eq. (2).

$$Nu_{\text{straight}} = 0.321 \cdot Re_d^{0.58} \quad (2)$$

A general uncertainty analysis was performed for the experimental data using the method described by Coleman and Steele [10]. The uncertainty had both bias (systematic) and precision (random) components. The major component of the uncertainty in Reynolds number was the combined bias of both static and stagnation pressure of 5.1% estimated from Fig. 6.29 of White [11]. This bias came from the misalignment of the pitot tube in the air stream for less than 10°. The uncertainty in Nu number came from the uncertainty in mass measurement, temperature measurement and bend radius measurement. The precision error of mass measurement was estimated by dividing the largest mass fluctuations observed by the actual mass collected during the measuring interval. The random scatter in the temperature measurements for Type K thermocouples was of the order 2%, and the measurement of bend radius was assumed to have a bias of 3%. The overall uncertainty in the measurement was 5.8% for Reynolds number and 11.3% for Nu number, with 95% confidence level. For more detailed uncertainty analysis, see Harris [2].

As shown in Fig. 4, all the measurements lie near Žhukauskas correlation within their uncertainty range. Therefore, the measurement should adequately predict

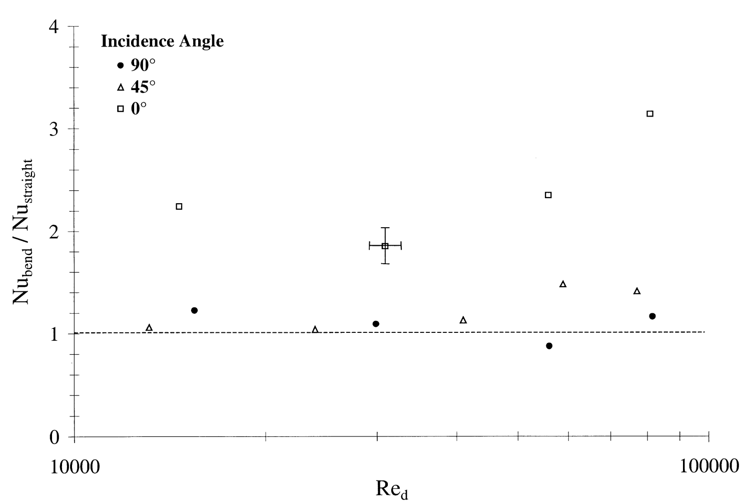

Fig. 5. Measured U-bend external heat transfer at 0, 45, and 90° angles-of-incidence.

the external heat transfer behavior on curved U-bend surfaces within the stated uncertainty limits.

3. Test results and discussion

Fig. 5 shows the reduced measurements at three angles-of-incidence reported by Harris and Goldschmidt [1]. The reduced measurements (Nu_{bend}) are presented with respect to the measured values for the straight pipe ($N_{straight}$) sections obtained during the validation phase. At the angle-of-incidence of 0°, the external heat transfer for the U-bend was 1.7–3 times the rate observed for straight pipe sections in cross flow

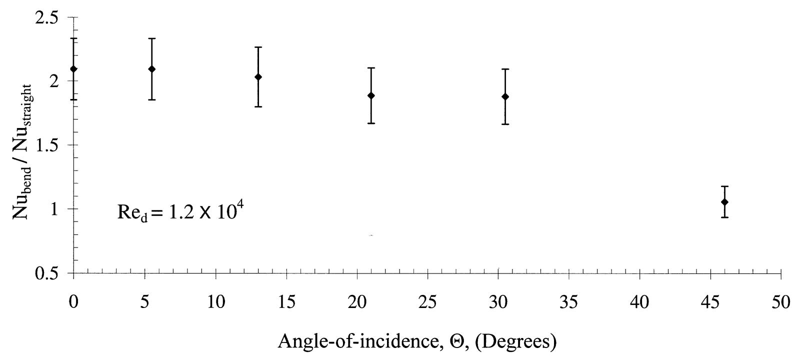

Fig. 6. Measured U-bend external heat transfer at different angles-of-incidence between 0 and 45° (I).

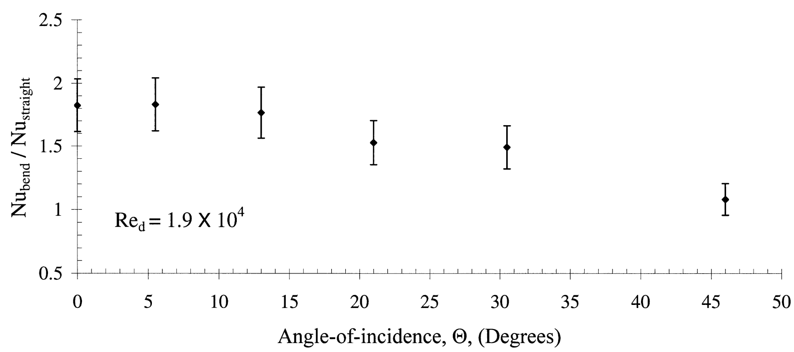

Fig. 7. Measured U-bend external heat transfer at different angles-of-incidence between 0 and 45° (II).

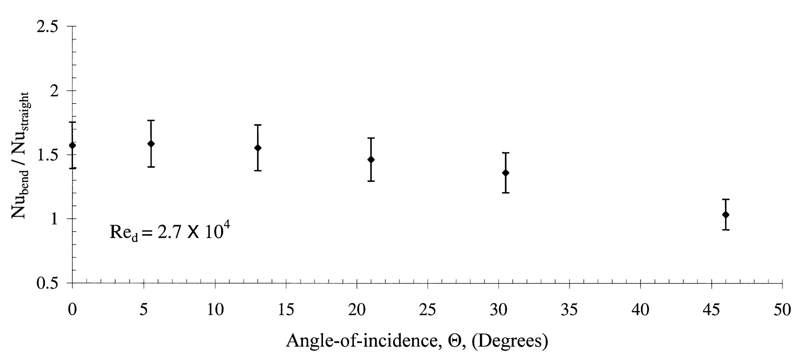

Fig. 8. Measured U-bend external heat transfer at different angles-of-incidence between 0 and 45° (III).

during the validation phase. There also appeared a distinct Reynolds number dependence on the level of this increase. It is evident that at 90° angle-of-incidence, the U-bend behaved similarly as straight pipe sections in cross flow. Also, at 45°, the U-bend behaved similarly as at 90°. Thus, it was expected that if the angle-of-incidence was between 45 and 90°, the heat transfer from a U-bend would be the same as that from a circular cylinder in cross flow since the rear part of the bend would be out of the wake region of the front part of the bend. In order to find out the behavior of the U-bend when the angle-of-incidence is between 0 and 45°, additional experiments were performed, and their results are described below.

Figs. 6–8 shows the heat transfer of the U-bend at six different angles-of-incidence and three different Reynolds numbers. It was found that heat transfer rate was maximum near 0° angle-of-incidence. There was a slight increase of heat transfer around 5° compared to 0°, but that, regardless of being a consistent trend, was within the range of experimental uncertainty. The maximum heat transfer rate for U-bend was 1.6–2.1 times the rate observed for straight pipe sections during validation phase, which agreed well with the results in Fig. 5. There was also a Reynolds number dependence on the ratio of the U-bend heat transfer rate compared to that of straight pipe sections during validation phase, which was also observed by Harris and Goldschmidt [1], Fig. 5. As the angle-of-incidence increased, the heat transfer rate decreased gradually. The heat transfer of the U-bend behaved similarly as a circular cylinder when the angle-of-incidence reached about 45°, just as the previous experiments in [1] had shown.

It was evident that the angle-of-incidence of external flow had an observable influence on the heat transfer of the U-bend. For all the three Reynolds numbers experimented, the maximum heat transfer rate occurred around 0–5° angle-of-incidence. The increase of heat transfer could be attributed to the wake effect of the front part of the bend on its rear section, as previously argued by Harris and Goldschmidt [1]. As the angle-of-incidence increased, the rear part of the bend gradually moved out of the wake region of the front part of the bend, therefore, the heat transfer rate of the bend gradually approached the value of a circular cylinder in cross flow. In summary, the optimal orientation of a U-bend in the cross flow was near 0° angle-of-incidence, when the external flow velocity vector was parallel to the bend plane.

4. Conclusion

The overall external heat transfer of a U-bend was found to depend on the angle-of-incidence and Reynolds number. The maximum heat transfer from a U-bend was achieved when the external flow velocity was nearly parallel to the plane of the bend. The rate of maximum external heat transfer from the U-bends was 1.6–3.2 times that of a circular cylinder in cross flow for Reynolds number range between 1×10^4 and 8×10^4. The rate was also found to be Reynolds number dependent.

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References

[1] D.K. Harris, V.W. Goldschmidt, An empirical investigation into the external heat transfer of a U-bend in cross flow, Int. J. of Heat and Mass Transfer 42 (11) (1999) 1957–1968.

[2] D.K. Harris, Heat transfer process for serpentine tabular heat exchangers, PhD thesis, Purdue University, West Lafayette, IN, 1997.

[3] T. Igarashi, Characteristics of the flow around two circular cylinders arranged in tandem, Bulletin of JSME 24 (188) (1981) 323–331.

[4] Z.G. Kostić, S.N. Oka, Fluid flow and heat transfer with two cylinders in cross flow, Int. J. of Heat and Mass Transfer 15 (1970) 279–299.

[5] P.M. Daujotas, J.J. Ziugzda, J.J. Saviskas, Heat transfer of a system of two cylinders differently oriented in a flow, Heat Transfer — Soviet Research 17 (2) (1985) 27–32.

[6] S. Aiba, Heat transfer from the downstream cylinder of two circular cylinders near a plane wall in a cross flow of air, Heat Transfer—Japanese Research 19 (3) (1990) 40–51.

[7] R. Hilpert, Forsch, Geb. Ingenieurwes 4 (1933) 215x.

[8] A. Žukauskas, Heat transfer from tubes in cross flow, in: J.P. Harnett, T.F. Irvine Jr. (Eds.), Advances in Heat Transfer, 8, Academic Press, New York, 1972.

[9] S.W. Churchill, M.A. Bernstein, A correlation equation for forced convection from gases and liquids to a circular cylinder in cross flow, J. of Heat Transfer 90 (1977) 300–306.

[10] H.W. Coleman, W.G. Steele Jr., Experimentation and Uncertainty Analysis for Engineers, Wiley, New York, 1989.

[11] F.M. White, in: Fluid Mechanics, 2nd ed., McGraw-Hill, New York, 1986, pp. 353–354.