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On the prediction of pressure drop across banks of inclined cylinders

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Abstract

This paper proposes a new way to predict the pressure drop across banks of inclined cylinders as a function of the inclination angle β relative to the mainstream. With the inclination chosen as the only variable, the flow orientation (due to anisotropy), open flow area ratio and porosity of the cylinder banks are maintained to be constant. An empirical correlation for the pressure loss behavior in the banks of inclined cylinders is made based on a characteristic length which varies in a sinusoidal manner as the inclination, combined with the principle of independence. This selection of the characteristic length is introduced to satisfy the constant porosity condition for the cylinder bank. It is shown that by including this characteristic length, the principle of independence applies: all non-dimensional pressure drop data collapse onto a single master curve regardless of the inclination angle for the Reynolds numbers (based on the characteristic length) ranging from 10^3 to 10^4. Consequently, this correlation allows the pressure drop for the inclination from 0° to 45° to be predicted for a given flow velocity.

Keywords: Pressure drop; Inclined bank of cylinders; Variable unit cell length; Principle of independence

1. Introduction

Circular cylinder banks have been widely used as heat exchangers in, for example, turbine engine blades and electronic devices. This is due to their simple manufacturing route, cost effectiveness and availability in various materials. This, in turn, has led to a substantial amount of research conducted to characterize the pressure drop and heat transfer in cylinder banks, including the work of Fowler and Bejan (1994) for low Reynolds numbers ($Re_d < 30$), Groehn (1981) for high Reynolds numbers ($3 \times 10^3 < Re_d < 5 \times 10^4$), and Zukauskas (1987) for a wide range of Reynolds numbers ($10^2 < Re_d < 10^6$) where d is the diameter of the cylinders.

In most of the research including the present study, the cylinder banks are confined in a flow channel and are subjected to forced convection. The thermal and hydraulic performances of the cylinder banks are found to be dependent on a range of factors: configuration (e.g., in-line or staggered arrays), spacing (e.g., transverse and longitudinal pitches), ratio of cylinder length to cylinder diameter, and yawed and inclined angles.

The aim of this paper is to study the hydraulic performance of inclined cylinder banks with respect to the mainstream. Fowler and Bejan (1994) performed numerical simulations, as well as experimental measurements, and found that the inclination of the cylinder banks is beneficial especially when both the pressure drop and heat transfer are of interest. This is due to the fact that the variation of the pressure drop as the inclination is changed is greater than that of the heat transfer. A smaller reduction in the rate of heat transfer than in the pressure drop due to inclination is achievable.

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Nomenclature

A, C, D	empirical constants
d	diameter of individual cylinder (m)
D_h	hydraulic diameter of test channel (m)
f	friction factor $= (\Delta P/L)D_h/(0.5\rho U^2)$
K_{Cell}	pressure loss coefficient $= (\Delta P/L)S_X(\beta)/(0.5\rho U^2)$
$K_{Cell,N}$	pressure loss coefficient using normal velocity component $= (\Delta P/L)S_X(\beta)/(0.5\rho U^2\cos^2(\beta))$
L	channel length (m)
$\Delta P/L$	pressure drop across channel length (Pa/m)
Re	Reynolds number
$S_X(\beta)$	longitudinal pitch used as unit cell length (m)
S_Y	transverse pitch of cylinder bank unit cell (m)
S_{XY}	staggered centerline pitch of cylinder bank unit cell (m)
U	mean inlet flow velocity (m/s)

Greeks

α	empirical deviation factor
β	inclined angle (degree)
ε	porosity
μ	viscosity
υ	kinetic viscosity
ρ	density

Effect of the inclined angle of the cylinder banks is implicitly contained within the pressure drop and heat transfer data. Since a single length scale such as the channel hydraulic diameter or cylinder diameter is typically used as a characteristic length for all different inclination angles, it is necessary to develop a way to extract the effect of the inclination angle from the amalgam of experimental data.

Several analytical approaches have been made to predict both the heat transfer and the pressure drop as a function of the inclination angle. These are mainly based on the principle of independence which considers only the velocity component normal to the cylinder axis. This is because, for an infinitely long cylinder, the velocity component parallel to the cylinder axis plays no part in the flow. For in-line cylinder banks, Groehn (1981) reported that whilst the heat transfer performance could be well predicted using the principle of independence, its prediction of the pressure drop is not favorable. Fowler and Bejan (1994) found, however, that the use of this principle at low Reynolds numbers ($Re_d < 30$) leads to an overprediction of the heat transfer in comparison with numerical simulations. This implies that the use of the principle of independence for the prediction of both heat transfer and pressure drop is still controversial.

The main objective of this study is to develop a new way to present experimental results in order to explicitly extract the effect of the inclination on pressure drop. A further aim is to examine a possible method to predict the pressure drop for arbitrary inclinations.

2. Inclination of cylinder banks

2.1. Staggered cylinder banks with inclination

A group of parallel cylinders configured in the staggered manner and confined in a rectangular channel is considered. It is immersed in an air flow as shown in Fig. 1(a). The geometrical parameters used to classify the cylinder bank are the longitudinal pitch ($S_X(\beta)$) and transverse pitch (S_Y), as illustrated in Fig. 1(b) and (c).

As aforementioned, the inclination of the cylinder banks is beneficial due to the fact that the variation of the

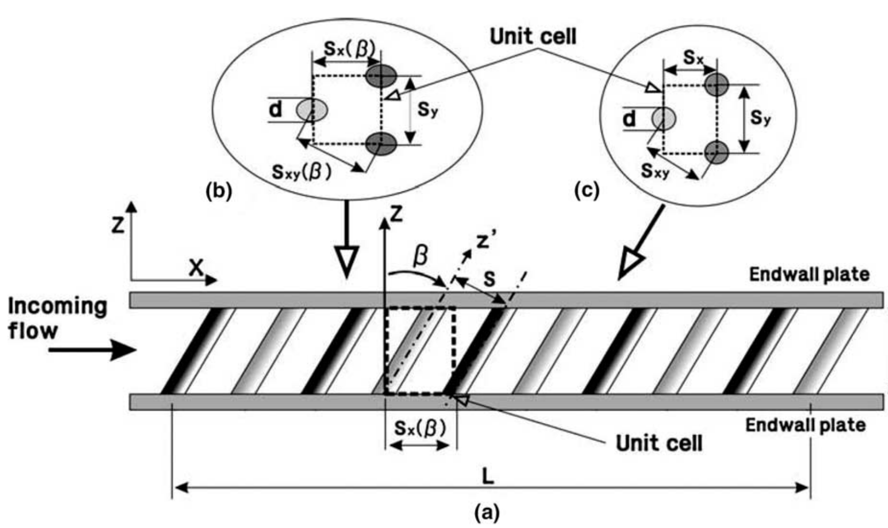

Fig. 1. Staggered cylinder bank with finite inclination angle: (a) sideview of cylinder bank; (b) planview of unit cell; (c) projection view along cylinder axis.

pressure drop with the inclination is greater than that of the heat transfer. Here, the inclination angle refers to an angle β measured from a plane perpendicular to the mainstream so that, when the cylinder axis is normal to the mainstream, $\beta = 0°$.

Two different methods can be used to change the inclination of a cylinder bank. One is to fix both ends of the cylinders to the endwall plates, as used by Fowler and Bejan (1994). When the lower endwall plate is shifted longitudinally and upward, the angle between the mainstream and the cylinder axis increases. During this inclination, the cylinder length remains unchanged, but the distance between the axes of adjacent cylinders and that between the top and bottom of the channel are changed. As a result, the porosity of the cylinder bank decreases (see Section 4 later). Another way, which is employed in this study, is to fix the channel height and rotate the cylinder bank with respect to the y-axis (see Fig. 1). The consequence is that the distance between the axes of adjacent cylinder is unchanged, leading to a constant porosity. The authors believe that this is a more appropriate method since the porosity is often directly related to the cost and weight of the heat exchangers.

2.2. Use of porosity in cylinder bank study and a unit cell consideration

Fowler and Bejan (1994) argued that if the cylinder bank is assumed to be a porous medium, then the use of porosity (void fraction) may provide a better parameterized view of the pressure drop behaviour in the bank. However, it should be noted that according to the definition of porous media (see, for example, Nield and Bejan (1999)), the cylinder banks are, in fact, not porous media. On the other hand, as examined by Kim (2004) and Kim et al. (2004a,b), when the flow passing an anisotropic structure is considered while the frontal area which the flow sees is fixed, the spacing along the flow direction can change flow characteristics. For such a case, the porosity can be used as a reference parameter when presenting the pressure drop characteristics although the idea of porosity stems from volumetric considerations.

Consider now the topology of the cylinder bank as shown in Fig. 1. The flow pattern in a single unit cell consisting of three cylinders (Fig. 1(c)) is expected to be repeatable excluding the cells near the entry and exit regions (Kim et al. (2002)). This unit cell consideration together with the porosity concept will be used below.

The porosity, ε (void fraction), is defined based on the configuration of Fig. 1 as

$$\varepsilon = 1 - \frac{\pi}{4\cos(\pi/6)}\left(\frac{d}{S_{XY}}\right)^2 \approx 1 - 0.907\left(\frac{d}{S_{XY}}\right)^2 \quad (1)$$

where d is the cylinder diameter and S_{XY} is the centerline distance between cylinders in a staggered-cell. This distance S_{XY} is set to be constant for the cylinder bank models examined in this paper.

Eq. (1) indicates that if ε and d are invariant, then the centerline distance (S_{XY}) between the cylinder axes in the projection view (Fig. 1(c)) does not change with the inclination angle (β). Only the distance in the longitudinal direction (x-axis), $S_X(\beta)$, depends on β in order to keep the porosity constant. This variation is expressed as

$$S_X(\beta) = \frac{S_X(0)}{\cos(\beta)} \quad (2)$$

where $S_X(0)$ is the longitudinal pitch of the non-inclined cylinder bank (i.e., $\beta = 0°$) and later will be used as the unit cell length.

In summary, for a fixed orientation of the anisotropic cylinder bank, it is necessary to set the following constraints for the systematic variation of the inclination:

(1) Frontal area of the cylinder arrays that the flow sees is fixed by setting the transverse pitch (S_Y) unchanged so that the flow area that is blocked by the cylinders is independent of the inclination. It should be noted that the cylinders are inclined with respect to the direction of the mainstream flow.
(2) Porosity is fixed regardless of the inclination. This implies that the longitudinal pitch $S_X(\beta)$ varies with the inclination according to Eq. (2).

It is believed that under these conditions the inclination angle is the only variable which influences the flow pattern in the channel.

3. Experimental setup

For the experimental measurements, a suction type windtunnel with 9:1 contraction and flow developing parallel channel before a test section was constructed (see Fig. 2). Before the contraction, a single layer of screen and a honeycomb were placed. The test section is 0.145 m wide, 0.012 m high and 0.29 m long.

Stagnation probe and static pressure tapping were used to measure the flow velocity. The static pressure tapping, 0.5 mm in diameter, was drilled into the top channel surface (Fig. 2). The stagnation pressure probe with a 0.25 mm inner diameter was inserted at the same x location (i.e., flow direction) as the static pressure tapping: they were placed in the centre of the channel at the test section inlet. To monitor the mainstream velocity profile, the stagnation pressure probe was traversed along the channel height (z-axis). The velocity profiles across the channel were used to calculate the mean flow velocity over a range of Reynolds numbers.

Wall interference effects on the stagnation pressure probe were expected to be small because the blockage ratio, i.e., ratio of channel height $H = 12$ mm to the outer diameter of the probe (=0.51 mm), was 23.5. Acrylic plates were used to fabricate the channel side and endwall surfaces. Plastic cylindrical bars of 3.25 mm diameter were used to

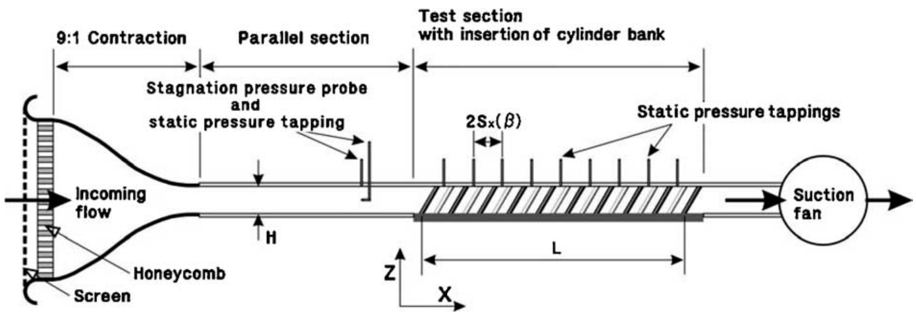

Fig. 2. Schematic of test rig.

Table 1
Details of inclined cylinder bank models ($d = 3.25$ mm for all cylinder bank models)

Inclined angle (β deg.)	Porosity (ε)	Transverse cell pitch (S_Y, mm)	Staggered-cell center line distance (S_{XY}, mm)	Longitudinal cell pitch ($S_X(\beta)$, mm)	AR ($= l/d$)
0	0.9	9.79	9.79	8.48	3.69
15				8.78	3.82
30				9.79	4.26
45				11.99	5.22

construct the cylinder bank models, all configured in staggered manner.

For the measurement of the pressure drop along the mainstream direction, static pressure tappings were placed on the upper channel endwall surface after every two cylinder rows, as shown in Fig. 2, so that the distance between the probes is $2S_X(\beta)$. In total, four test models with 0°, 15°, 30°, and 45° of inclination were fabricated. Details of the test models are presented in Table 1.

The pressure tubes of the stagnation probe and static pressure tappings were connected to a 48 port *J*-type Scanivalve™. The pressure signals were then sent to an A/D card (PCI-M10-16E, National Instruments Inc.) in a data logging PC. A Labview™ data acquisition program monitored and recorded the data. It also controlled the Scanivalve™ via a RS232 cable.

4. Results and discussion

4.1. Presentation of pressure drop across the cylinder banks

In common practice, the pressure drop across most of heat exchangers confined in a flow channel is expressed as the pressure drop per unit length ($\Delta P/L$). The corresponding nondimensional friction factor, f is defined as

$$f = \frac{\Delta P}{L}\frac{D_{\rm h}}{\rho U^2/2}$$

where ρ is the fluid density, U is inlet fluid velocity, ΔP is the static pressure drop over distance L and $D_{\rm h}$ is the hydraulic diameter of the channel calculated from $4WH/(2(H+W))$, with W and H representing the channel width and height respectively. The hydraulic diameter of the test channel in this study is 0.0221 m.

Fig. 3(a) plots the pressure drop per unit length $\Delta P/L$ as a function of flow velocity for selected inclination angles of 0°, 15°, 30° and 45°; the corresponding friction factor f is plotted in Fig. 3(b) as a function of the Reynolds number $Re_{D_{\rm h}}$, defined as

$$Re_{D_{\rm h}} = \frac{UD_{\rm h}}{\upsilon}$$

where υ is the kinetic viscosity of the fluid. The hydraulic diameter of the flow channel was used for plotting both figures. Measurement uncertainties due to random errors in the pressure drop and friction factor were estimated to be less than 0.1% and 1.7%, respectively. These were estimated in 95% confidence interval and performed using the method of Coleman and Steele (1999).

Fig. 3 clearly shows that a higher inclination causes a smaller pressure drop and hence a lower value of the friction factor. In other words, it is beneficial to incline the cylinders as this reduces the pressure drop.

4.2. Pressure drop per unit cell using a variable unit cell length

Kim et al. (2004a,b) observed that in many periodic structures the flow patterns repeat in each unit cell, excluding the cells near the entry and exit regions. Thus, information related to a representative unit cell can be utilized to express the overall hydraulic behavior of the structures. This concept has been successfully applied to lattice-frame materials (Kim et al., 2004a) and cellular foams (Kim et al., 2002). Similarly, the pressure drop across a cylinder bank may be expressed in terms of a new parameter $K_{\rm Cell}$. This represents the static pressure drop over a unit cell of the cylinder bank, as

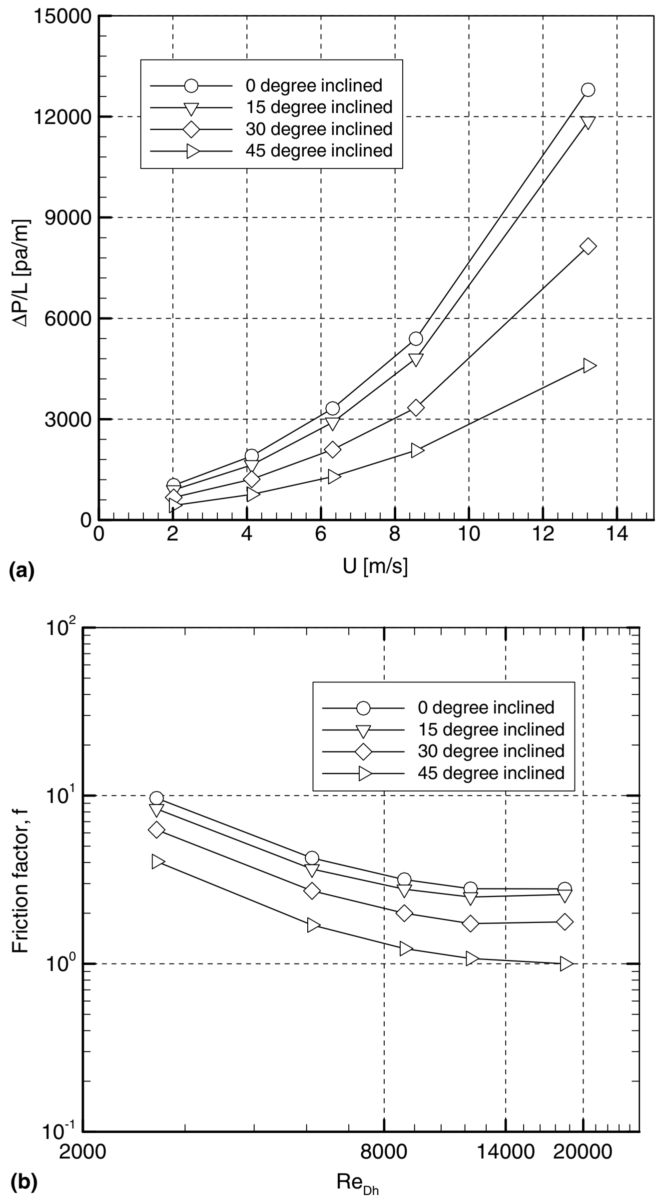

Fig. 3. Pressure drop performance of inclined cylinder banks: (a) Pressure drop per unit length plotted as a function inlet flow velocity; (b) friction factor plotted as a function of the Reynolds number (based on hydraulic channel diameter) for selected values of the inclination angle.

$$K_{\text{Cell}} = \frac{\Delta P_{\text{Cell}}}{\rho U^2/2} \quad \text{and} \quad \Delta P_{\text{Cell}} = \left(\frac{\Delta P}{L}\right) S_X(\beta) \tag{3}$$

where $S_X(\beta)$ is the unit cell length. During the design of a heat exchanger, for example, it is necessary to know the overall pressure drop across the heat dissipation medium. To this end, K_{Cell} would be multiplied by the number of unit cells in the flow direction. The Reynolds number based on the unit cell length is defined as

$$Re_{Sx(\beta)} = \frac{US_X(\beta)}{\nu}$$

Fig. 4 plots the pressure loss coefficients as a function of Reynolds number for four inclination angles: 0°, 15°, 30° and 45°. The variable unit cell length was used as the reference length instead of the channel hydraulic diameter typically used. Unlike Fig. 3(b) showing the conventional friction factor, Fig. 4 clearly indicates flow transition from laminar to form-dominated flow. Although the four cylinder bank models have similar trend at low Reynolds numbers, they have different transitional Reynolds numbers, depending on the inclination angle. Within the laminar flow regime ($10^3 < Re_{Sx(\beta)} < 2 \times 10^3$), the pressure drop is, as expected, inversely proportional to the Reynolds number:

$$K_{\text{Cell}} = \frac{A}{Re_{Sx(\beta)}}$$

where the empirical constant A was found to be approximately 3400. After transition, the pressure loss coefficient of each cylinder bank appears to approach an asymptotic value in high Reynolds number region ($Re_{Sx(\beta)} > 4 \times 10^3$). Its magnitude depends on the degree of inclination, showing a higher pressure loss for a smaller inclined angle.

In summary, each inclination angle causes differences in the onset value of the transitional Reynolds numbers and in the magnitude of K_{Cell} at higher Reynolds numbers. In addition, in the laminar regime, all cylinder banks behave hydraulically in a similar manner, regardless of their inclination angles with respect to the mainstream.

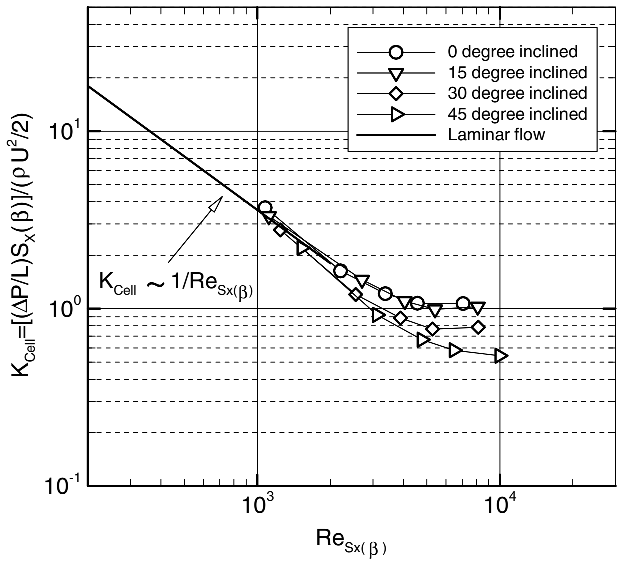

Fig. 4. Effect of the inclined angle on the pressure loss coefficients in the range of Reynolds number, $10^3 < Re_{Sx(\beta)} < 10^4$.

4.3. Applicability of the principle of independence

For the flow around infinitely long inclined cylinders, there is a theoretical solution, stating that the flow is independent of the axial direction of the cylinder. This is known as the 'principle of independence'. Experimental validations of the principle were reported by many researchers. Groehn (1981) and Zukauskas (1987) first studied a single cylinder in the laminar flow regime, and found that the normalized pressure distribution is independent of the inclination angle. A further investigation of the validity of the principle for cylinder banks was conducted. Groehn (1981) concluded that the principle is valid for heat transfer in inclined cylinder banks whereas its use for describing the pressure drop behaviour is improper.

Conventionally, the pressure drop is expressed by the ratio

$$\frac{\Delta P(\beta)/L}{\Delta P(0)/L} = \cos^{2+\alpha}(\beta)$$

where α is an empirical deviation factor. This ratio is used to examine quantitatively the effect of inclination angle on the pressure drop across a cylinder bank. If the principle of independence is valid, then $\alpha = 0$. It has nonetheless been accepted that the empirically determined value of α is non-zero (Groehn, 1981). This indicates that the principle of independence may not be valid when the prediction of the variation of the pressure drop with varying β is of concern.

For the present cylinder bank models, the pressure drop per unit length is plotted as a function of the inclination angle in Fig. 5 (empty square points) for $Re_{Sx(\beta)} = 7.0 \times 10^3$. A solid curve referred as "$\cos^2(\beta)$" based on the principle of independence is also included in this figure. It is evident from Fig. 5 that the principle of independence appears to overestimate the pressure drop. This is consistent with the conclusion reached by Groehn (1981).

Fig. 5 also shows the ratio of the pressure loss coefficients, $K_{\text{Cell}}(\beta)/K_{\text{Cell}}(0)$. The data points are found to correlate well with the prediction using the principle of independence. This new-found agreement occurs because the pressure difference (ΔP) is measured between two fixed longitudinal locations having a separation distance of L. Many unit cells are contained within this distance. If the inclination method considered both in this study and in Groehn (1981) is used, the number of unit cells would decrease in order to satisfy the constant porosity constraint. Although the conventional friction factor cannot account for this change, the pressure loss coefficient reflects this change by using the variable unit cell length $S_X(\beta)$.

For a further confirmation of this finding, test data from Groehn (1981) are reproduced in Fig. 6 using the variable unit cell length together with the original data. Although the cylinder banks studied by Groehn (1981) were arranged in-line, they were inclined in the same way as that used in the present study. It should be noted that there is a difference though in the notation for the inclination: in Groehn (1981), 0° of inclination corresponds to the case when the cylinders are parallel to the mainstream while in this study 0° is set when the cylinders are normal to the mainstream.

In Fig. 6, the empty circular points are the measurements of Groehn (1981) and the solid curve is the prediction using the principle of independence. It is seen from this figure that the principle of independence does not appear to be valid. On the other hand, the filled square points indicate the converted data into the ratio of the pressure loss coefficients after multiplying the original data by a factor of $\cos(\beta)$. It is apparent that the converted test data fit very well with the principle of independence. This supports the usefulness of the variable unit cell length.

For inclined cylinder banks configured in both staggered and in-lined arrays, the results shown in Figs. 5 and 6 suggest that the principle of independence is valid and can be used to predict the pressure drop, provided that the variable unit cell length is used as a characteristic length.

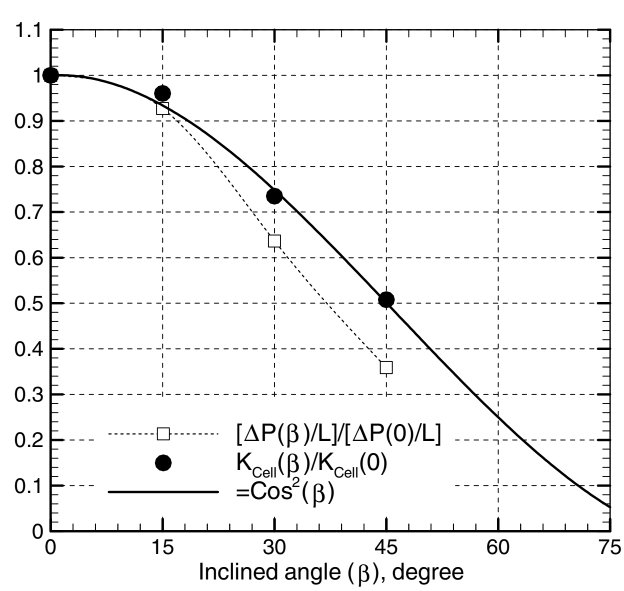

Fig. 5. Validity of the principle of independence in showing: effect of inclination angle on pressure drop at $Re_{Sx(\beta)} = 7.0 \times 10^3$.

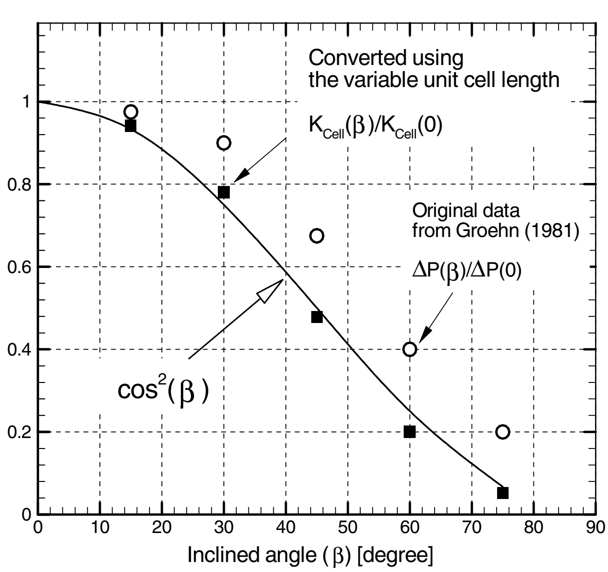

Fig. 6. Validity of the use of unit cell length as a characteristic length at $Re_{Sx(\beta)} = 2.0 \times 10^4$ (source data from Groehn (1981)).

4.4. Prediction of pressure drop in inclined cylinder banks

It appears that the use of both the variable unit cell length and the principle of independence provide good predictions of the pressure drop for a range of Reynolds numbers. A simple substitution of the mainstream velocity (U) by the normal velocity component $U\cos(\beta)$, which is an indication of the use of the principle of independence yields another form of Reynolds number and the pressure loss coefficient, as

$$K_{\mathrm{Cell},N} = \frac{(\Delta P/L)S_X(\beta)}{\rho(U\cos(\beta))^2/2} \quad \text{and} \quad Re_{Sx(\beta),N} = \frac{U\cos(\beta)S_X(\beta)}{\nu} \tag{4}$$

where $S_X(\beta)$ is the variable unit cell length and the subscript N denotes the use of normal velocity component. Fig. 7 plots $K_{\mathrm{Cell},N}$ as a function of $Re_{Sx(\beta),N}$ for the four cylinder banks tested in this study. It is seen that the pressure loss coefficients obtained from all inclined cylinder banks collapse onto a single curve, at least for the range of Reynolds numbers, $10^3 \leqslant Re_{Sx(\beta),N} \leqslant 7.0\times10^3$. The curve was empirically correlated as

$$K_{\mathrm{Cell},N} = \frac{C}{Re_{Sx(\beta),N}} + D \tag{5}$$

where C and D are empirical constants found to be 3400 and 0.4 respectively in the present study. This correlation gives a reasonable representation within ±15% deviation.

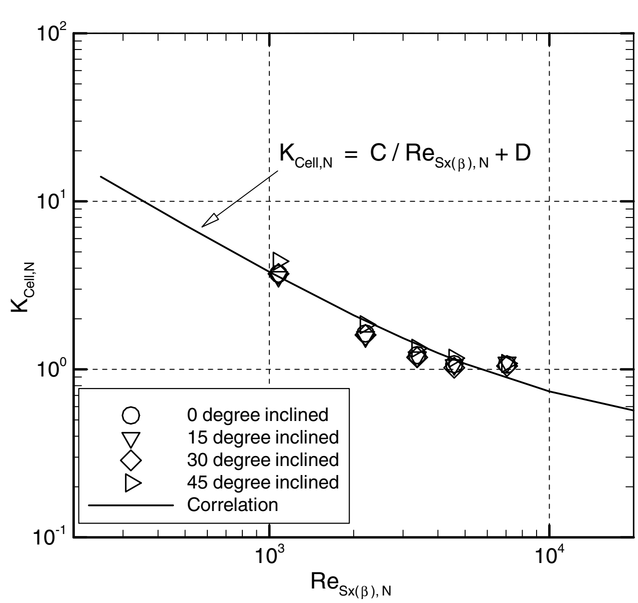

Fig. 7. Pressure loss coefficient plotted as a function of Reynolds number, both expressed using the normal velocity component $U\cos(\beta)$ and the unit cell length $S_X(\beta)$.

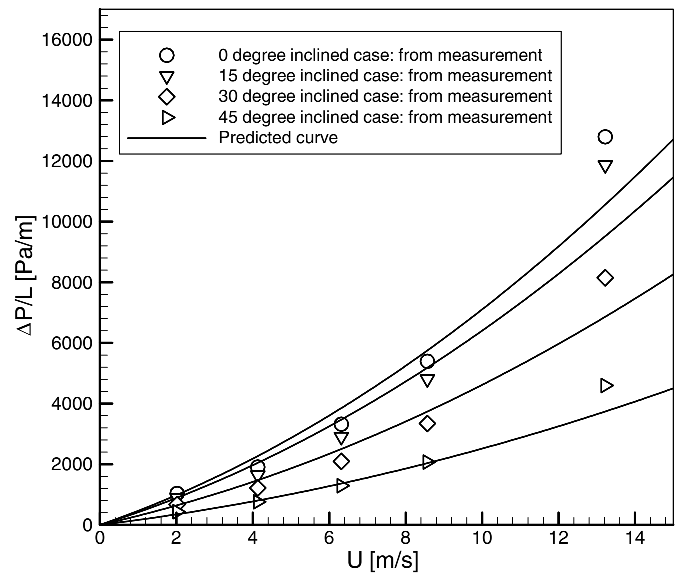

Fig. 8. A comparison of the measured pressure drop data $\Delta P/L$ to those obtained from Eq. (6).

After mathematical manipulation of Eq. (5), the pressure drop per unit length ($\Delta P/L$) for an arbitrary inclined angle can be expressed as

$$\frac{\Delta P}{L}(\beta) = \left[C\left(\frac{\mu}{2S_X(0)^2}\right)U + D\left(\frac{\rho}{2S_X(0)}\right)U^2\right]\cos^3(\beta) \tag{6}$$

where $S_X(0)$ is the unit cell length for the 0° inclined cylinder bank, β is an arbitrary value of the inclined angle ranging from 0° to 45° and μ is the fluid viscosity. Eq. (6) states that the pressure drop per unit length ($\Delta P/L$) can be expressed primarily as a function of the inclined angle β for a given flow velocity U and known fluid density ρ, viscosity μ, and the unit cell length for $\beta = 0°$, $S_X(0)$.

Fig. 8 shows comparison results of the measured pressure drop to the curves produced by Eq. (6) for four different inclined cylinder banks. The predicted values show good agreement with the experimental data, especially for fluid velocities less than 10 m/s. It can be said that the use of the unit cell length which varies with the inclination and the principle of independence thence allows the pressure loss in the banks of cylinders to be predicted regardless of the inclined angle, ranging from 0° to 45°.

This paper has underlined that in order to extract influence of the inclined angle on the pressure drop behaviour, a proper selection of characteristic length plays an essential role when presenting the results as we have found. The effects of the inclination angle on the thermal behaviour in the banks of cylinders will be presented in a future paper.

5. Summary and conclusions

In this paper we introduced a new way to present the experimentally measured pressure drop characteristics of flow across inclined cylinder banks. This was carried out by using the unit cell length to fulfil the two main conditions. These are that the frontal area (or open flow area ratio) of the cylinder arrays is fixed and that the porosity is fixed. With the unit cell length being used as a characteristic length, it is found that the principle of independence is valid for predicting the pressure drop across inclined cylinder banks configured in as staggered and as in-line arrays. Furthermore, the overall pressure drop behaviour can be predicted for any inclination angles ranging from 0° to 45° for the Reynolds numbers (based on the characteristic length) from 10^3 to 10^4.

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