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EFFECT OF A MISSING CYLINDER ON HEAT TRANSFER AND FLUID FLOW IN AN ARRAY OF CYLINDERS IN CROSS-FLOW

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Abstract—Experiments encompassing both heat transfer measurements and flow visualization were performed for cross-flow arrays of cylinders in which there is a missing cylinder. Both staggered and in-line arrays were investigated. The visualization work, carried out with the oil–lampblack technique, yielded highly revealing photographs of the patterns of fluid flow, both for fully populated arrays and for arrays which have a missing cylinder. With regard to heat transfer, it was found that a staggered array is more responsive to a missing cylinder than is an in-line array.

INTRODUCTION

THERE is a substantial literature on heat exchange devices which encompass arrays of cylinders in cross-flow [1–3]. Without exception, the available information pertains to regular arrays in which all elements of the array are present. The present investigation deals with departures from regularity, with specific consideration being given to the effect of a missing cylinder on the heat transfer and fluid flow characteristics of adjacent cylinders. The investigation has two parts. In one part, quantitative heat transfer measurements were made for cylinders situated adjacent to the site of the missing cylinder. In the other part, flow visualization was performed to explore the manner in which the fluid flow pattern in the array is affected by the missing cylinder. Experiments were conducted for both staggered and in-line arrangements.

EXPERIMENTS

The host flow passage for the array of cylinders was a flat rectangular duct, 8.26 × 1.91 cm (width × height) in cross-section, and 173 cm long. The overall length of the duct encompassed a hydrodynamic development section, the test section, and a downstream hydrodynamic redevelopment section.

The cylinders comprising the array were oriented perpendicular to the principal walls of the test section (i.e. the upper and lower walls) and were seated in holes in the lower wall. Interchangeable lower walls were fabricated with suitable hole arrangements to accommodate the in-line and staggered arrays. The staggered array was laid out in an equilateral triangular pattern, with $S_T/D = 3$ and $S_L/D = (\sqrt{3}/2)\,(S_T/D)$, where S_T and S_L are the transverse and longitudinal pitches, and $D = 0.556$ cm is the cylinder diameter. The in-line array was, in effect, a realignment of the staggered array with the values of S_T/D and S_L/D being maintained. In both cases, 18 rows of cylinders were employed. The heat transfer measurements were made in the 12th row, where fully developed conditions prevailed.

The cylinders used in the experiments were intended to model pin fins, and a small clearance gap (1/8 of the channel height) was left between the tips of the cylinders and the upper wall of the test section. Experiments reported in [4, 5], where the aforementioned staggered and in-line arrays were respectively employed in a fully populated state (without missing cylinders), yielded fully developed heat transfer coefficients that agreed very well with literature values for tube banks. On this basis, the present results for the effects of missing cylinders should also be relevant to tube banks. Air was the working fluid in all of the experiments.

Instead of direct heat transfer measurements, per-cylinder heat transfer coefficients were deduced by applying the heat/mass transfer analogy to mass transfer measurements performed via the naphthalene sublimation technique. The procedures for applying this technique for cylindrical pin fins are documented in [4], as is the data reduction process which converts mass transfer measurements to mass transfer coefficients and, by the analogy, to heat transfer coefficients.

The flow visualization was performed by means of the oil–lampblack technique. To facilitate the use of this technique, the lower wall of the test section was covered with white, plastic-coated contact paper, and holes were cut in the paper to accommodate the array of cylinders. Before insertion of the cylinders, the contact paper was brushed with a mixture of lampblack powder and oil of suitable consistency. Once the cylinders were inserted, the test section was sealed and the air flow activated. Under the action of the shear stresses exerted by the air flow, the oil–lampblack mixture was caused to move, thereby revealing the pattern of fluid flow adjacent to the lower wall of the test section.

RESULTS AND DISCUSSION

Flow visualization

The flow visualization photographs presented in Figs. 1(a, b) and 2(a, b) convey a record of the pattern of fluid flow adjacent to the lower wall of the test section. Each figure is a top view looking downward on the array, with the white circles corresponding to the locations of the cylinders and with the fluid flowing in the direction from the bottom to the top of the photograph. Figures 1(a, b) pertain to the staggered array. The first of these shows all of the cylinders in place, while in the second, one of the cylinders of the array is missing. Similarly, Figs. 2(a, b) pertain to the in-line array, respectively for all cylinders in place and for one cylinder missing.

In interpreting these photos, it should be noted that prior to the onset of the air flow, the entire field, except for the white circles, is a uniform, glossy black. The white streaks in evidence in the photos correspond to the path lines of the fluid flow, while zones of concentrated black color depict regions where the shear exerted by the fluid was too weak to move the oil–lampblack mixture. These black zones may be regarded as indicating low velocity regions.

In this regard, a special note of caution should be sounded about the somewhat irregular black annuli which surround the various holes. The respective annuli result, in large part, from an accumulation of the black mixture which was swept up against the cylinder when the air flow was initiated and was held there by the forces exerted by the flow. When the air flow was turned off, the mixture drained from the cylinder (due to gravity) and formed the black annulus

Examination of Fig. 1(a) reveals a remarkable regularity, both among the successive rows and across the span of the array in any given row (irregularities in the black annuli are extraneous, as just discussed). The row-by-row repetition of the flow pattern typifies the periodic fully developed regime. Regions of low velocity (i.e. black regions) exist both upstream and downstream of each cylinder in the array. The low velocity region upstream of the cylinder is due to the collision of two flows. One of these is the main-flow approaching the cylinder. The other is a back-flow which is induced by a gradient of pressure along the height of the cylinder. This pressure gradient drives fluid downward along the cylinder, causing it to splash against the lower wall of the test section. Part of the splashed flow moves forward into the path of the main-flow which passes adjacent to the wall, and the opposing flows create a low velocity region.

The low velocity region downstream of the cylinder is a buffer zone (i.e. an island of calm) between the recirculating flow situated immediately downstream of the cylinder and the main-flow which threads its way through the alley between diagonally positioned cylinders. The recirculating flow is readily identified by examination of the crown-like structure perched atop each cylinder (i.e. just downstream of the cylinder). The side-to-side symmetry of the crown is another indication of the spanwise periodicity of the flow field.

Figure 1(b), when compared with Fig. 1(a), provides an indication of the alteration of the flow which occurs when a cylinder is missing. The disturbance of the flow is seen to be quite localized. Fluid tends to pass longitudinally through the space formerly occupied by the now-missing cylinder, and it is evident that the flow adjacent to the two cylinders at the downstream end of the straight run is definitely affected, as witnessed by the outward canting of the crowns of these cylinders. Otherwise, the flow field does not seem to be much different from that pictured in Fig. 1(a).

For the fully populated in-line array [Fig. 2(a)], the expected tendency of the main-flow to course through the clear channels and to ignore the longitudinal intercylinder spaces is vividly displayed. The main-flow acknowledges the presence of the successive rows of cylinders by adopting a slightly undulating path, which pinches in when abreast of the cylinders and spreads out slightly when abreast of the intercylinder space. The fore portion of the intercylinder space is dominated by a recirculation zone while the aft portion (the black region) is a low velocity zone.

The removal of a cylinder [Fig. 2(b)] enables the main-flow to make a somewhat deeper incursion into the now-elongated intercylinder space. It is noteworthy, however, that the crowns of the two cylinders which stand at the right- and left-hand sides of the vacated space are not skewed, suggesting a minimal effect on these cylinders. The crown of the cylinder just upstream of the space is slightly truncated compared to the normal pattern, as is the low velocity region at the downstream end of the space. From the photographs alone, it is difficult to assess the importance of these seemingly minor changes.

Heat transfer results

The heat transfer results are presented in Figs. 3 and 4, respectively for the staggered and in-line arrays. Each figure displays the portion of the array which encompasses the missing cylinder, with the flow direction being from left to right as shown. As noted earlier, the heat transfer coefficients were measured in the twelfth row and correspond to the fully developed regime.

In each figure, each of the cylinders situated in the neighbourhood of the site of the missing cylinder is marked with two numbers, one above and one below. Each number represents the ratio of two heat transfer coefficients, with both coefficients corresponding to a given Reynolds number. The numerator of the ratio is the heat transfer coefficient for the case in which there is a cylinder missing from the array, while the denominator is the heat transfer coefficient when all cylinders are present. Thus, the departures of the listed

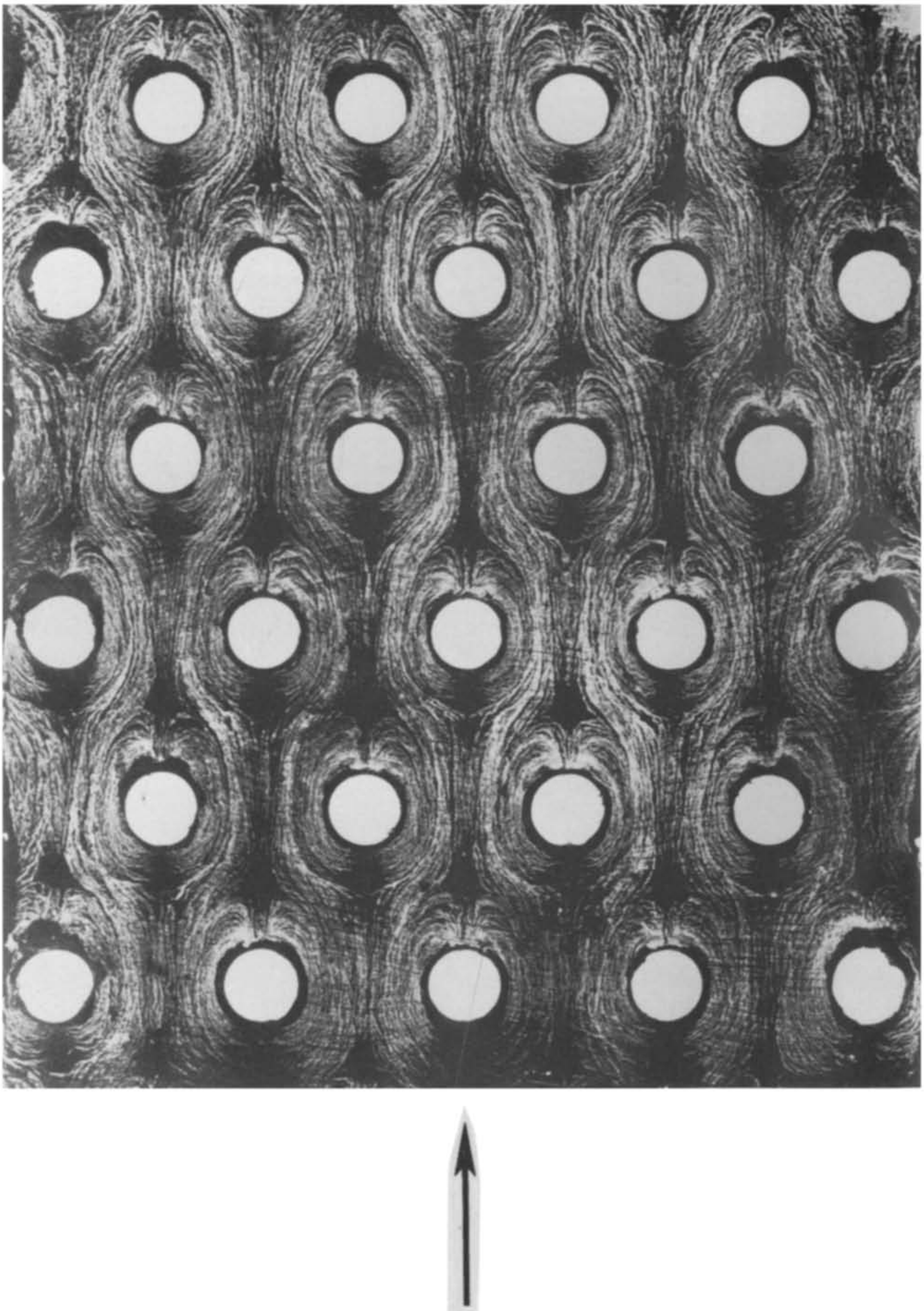

FIG. 1(a). Fluid flow pattern for a fully populated staggered array.

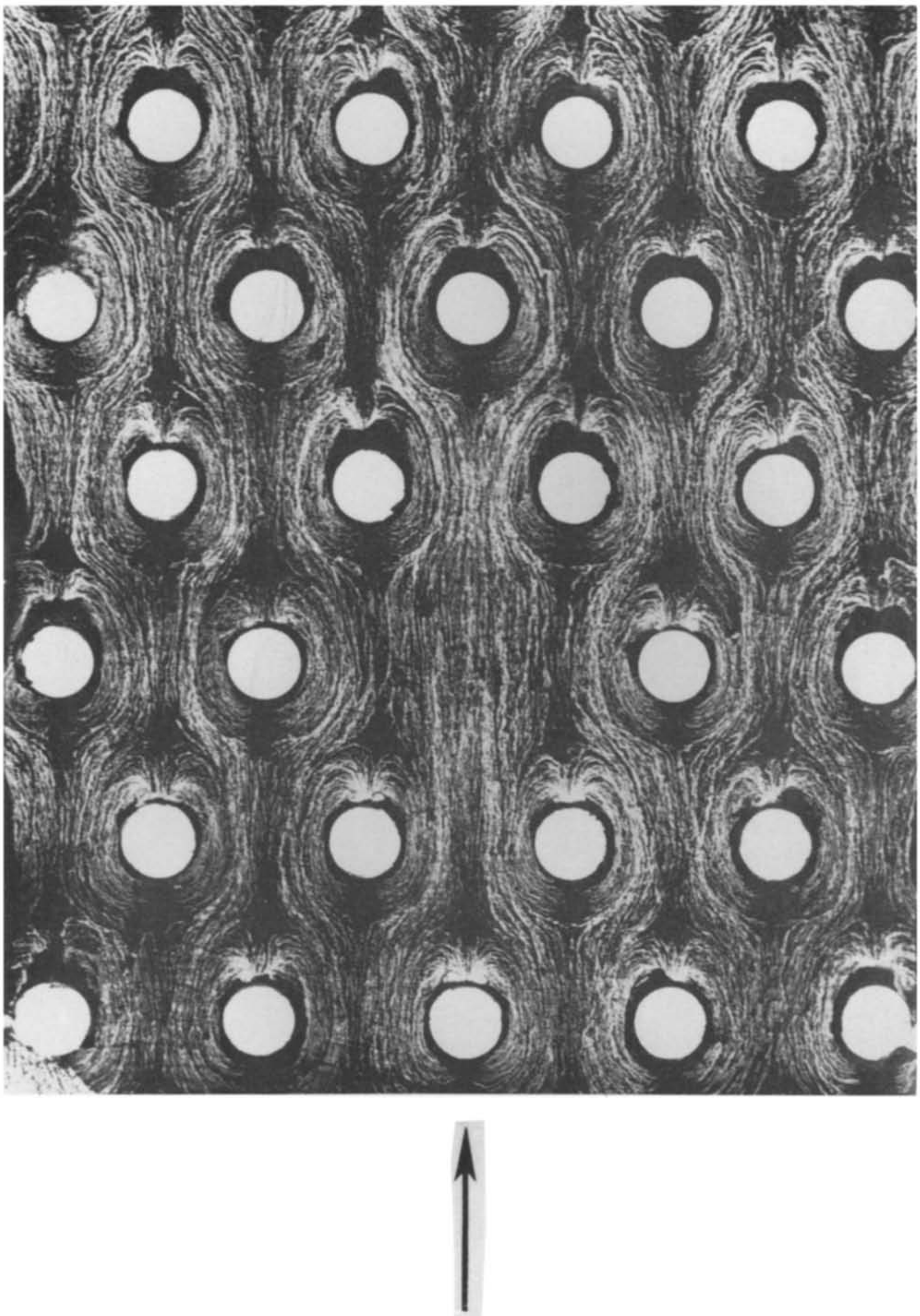

FIG. 1(b). Fluid flow pattern for a staggered array in which there is a cylinder missing from the array.

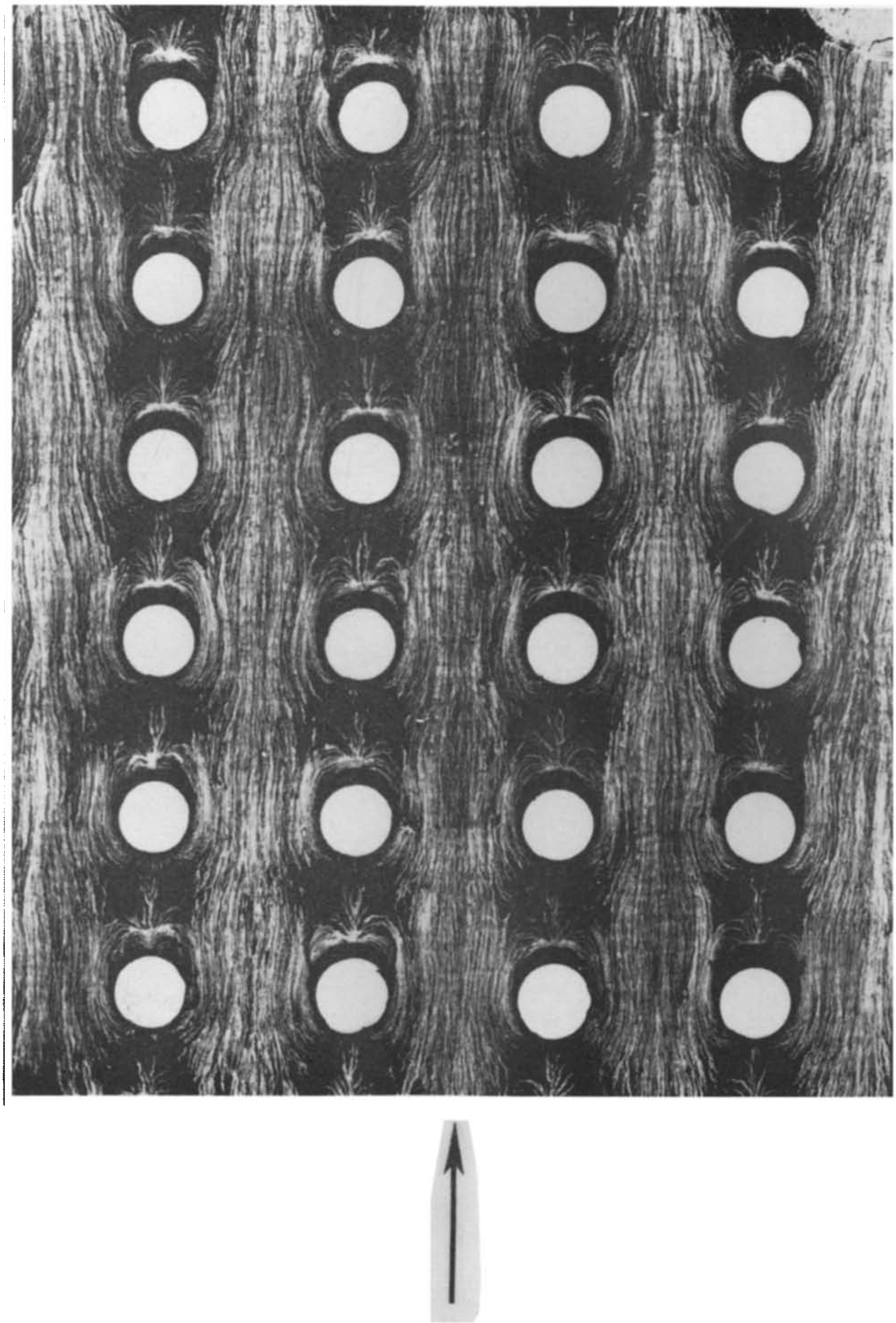

FIG. 2(a). Fluid flow pattern for a fully populated in-line array.

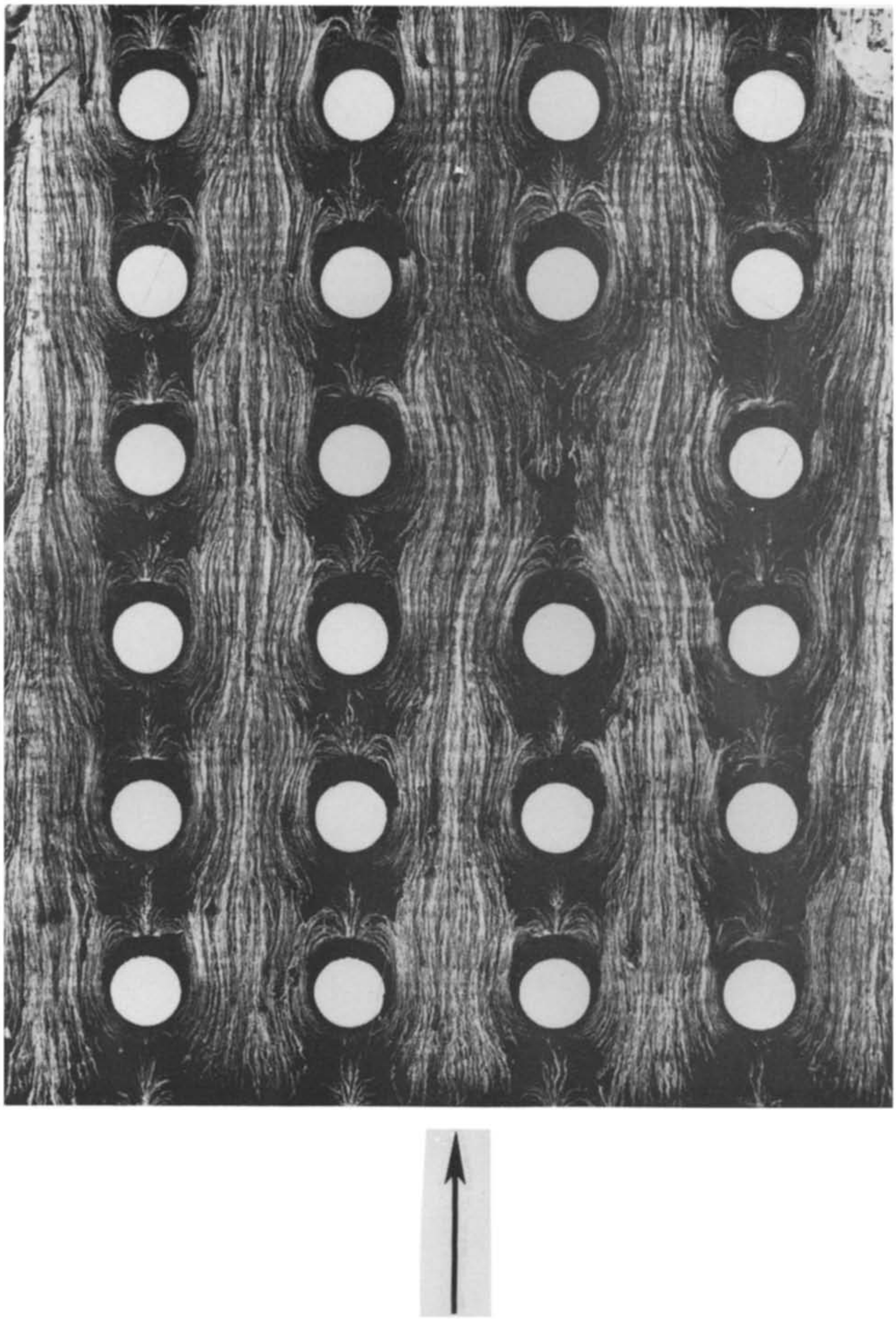

FIG. 2(b). Fluid flow pattern for an in-line array in which there is a cylinder missing from the array.

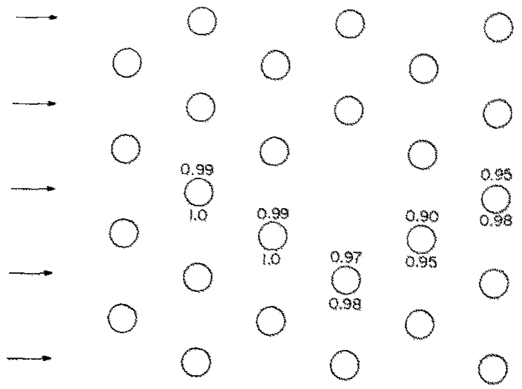

FIG. 3. Effect of a missing cylinder on the heat transfer coefficients at neighboring cylinders in a staggered array.

Fig. 4. Effect of a missing cylinder on the heat transfer coefficients at neighboring cylinders in an in-line array.

ratios from unity provide an immediate measure of the effect of the missing cylinder.

The results are parameterized by the Reynolds number, for which two distinct definitions have been employed. One of the Reynolds numbers is that for the duct without the cylinders in place. The other Reynolds number is based on the velocity through the minimum flow area of the array and on the cylinder diameter as the characteristic dimension. The two duct Reynolds numbers considered were 5000 and 35,000, with corresponding array Reynolds numbers of 1270 and 8900. In the figures, the numbers listed above the respective cylinders correspond to the higher of the two Reynolds numbers, while the numbers listed below are for the lower Reynolds number.

Turning first to the staggered array (Fig. 3), it is seen that the missing cylinder tends to reduce the heat transfer coefficients at the neighbouring cylinders, but for the most part, the reductions are very small. For cylinders located either to the side or forward of the vacated site, the reductions are in the 0–3% range. Only in the row immediately downstream of the vacated site is there a noteworthy effect—a 10% reduction at the higher Reynolds number. This reduction in the value of the transfer coefficient is the result of a lower impingement velocity and of a possible reduction of the turbulence level. That this row should be the most affected by the missing cylinder is in accord with comments made during the discussion of the flow visualization photographs.

Lesser reductions occur both to the side of the vacant site and at two rows downstream. These reductions are smaller because at these locations, either a decrease in velocity or lower turbulence may play a role, but both do not act simultaneously. The heat transfer coefficients at the lower Reynolds number appear to be less affected by the missing cylinder than are those at the higher Reynolds number.

Figure 4 shows that the heat transfer coefficients for the in-line array are quite insensitive to the missing cylinder. This finding is not surprising in light of the minimal modification of the flow field which occurs when a cylinder is removed from the array [Figs. 2 (a, b)].

In general, the irregularity caused by a missing cylinder does not result in significant changes in the heat transfer coefficients at the neighboring cylinders of the array.

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EFFET DE L'ABSENCE D'UN CYLINDRE SUR LE TRANSFERT THERMIQUE ET L'ECOULEMENT DE FLUIDE DANS UNE NAPPE FRONTALE DE CYLINDRES

Résumé—Des expériences sur le transfert thermique et sur la visualisation de l'écoulement ont été faites pour des nappes frontales de cylindres dans lesquelles un cylindre est manquant. On a étudié les arrangements en ligne et quinconcés. La visualisation à partir de la technique de la fumée avec suie conduit à des photographies très révélatrices des configurations d'écoulement aussi bien pour la nappe complète que pour celle à laquelle il manque un cylindre. Relativement au transfert thermique, on trouve que l'arrangement en quinconce est plus sensible à l'absence d'un cylindre que l'arrangement en ligne.

DER EINFLUSS EINES FEHLENDEN ZYLINDERS AUF WÄRMEÜBERGANG UND STRÖMUNGSFORM IN EINEM BÜNDEL VON ZYLINDERN BEI KREUZSTROM

Zusammenfassung—Experimente, die sowohl Wärmeübergangsmessungen als auch Strömungssichtbarmachung umfaßten, wurden für Kreuzstrom-Anordnungen von Zylindern durchgeführt, in denen ein Zylinder fehlte. Sowohl versetzte als auch fluchtende Anordnung wurden untersucht. Die Strömungssichtbarmachung nach dem Ölruß-Verfahren lieferte höchst aufschlußreiche Fotografien der Strömungsbilder für voll besetzte und für Anordnungen, in denen ein Zylinder fehlte. Im Hinblick auf den Wärmeübergang zeigte sich, daß eine versetzte Anordnung stärker auf einen fehlenden Zylinder reagiert als eine fluchtende.

ТЕПЛОПЕРЕНОС И ТЕЧЕНИЕ ЖИДКОСТИ ПРИ ИЗЪЯ.ИИ ОДНОГО ИЗ РАСПОЛОЖЕННЫХ В ПУЧКЕ ПОПЕРЕЧНО ОБТЕКАЕМЫХ ЦИЛИНДРОВ

Аннотация — Проведены экспериментальные измерения плотности теплового потока и визуализация течения в поперечно обтекаемом пучке цилиндров при изъятии из него одного цилиндра. Исследовались как шахматные, так и коридорные пучки. Визуализация потока методом нанесения мелкодисперсной сажи позволила получить очень четкие фотографии картины течения как для пучков с полным, так и с неполным набором цилиндров. Что касается теплообмена, то выяснилось, что отсутствие одного цилиндра больше сказывается в шахматном, чем в коридорном пучке.