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PRESSURE DROP PERFORMANCE OF ROD BUNDLES IN HEXAGONAL ARRANGEMENTS

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Abstract—Systematic investigations were carried out on the pressure drop for an incompressible, isothermal, fully developed turbulent flow in rod bundles with hexagonal arrangement of rods. The results of measurements of the pressure drop over a range of Reynolds numbers $Re = 6 \times 10^2$ – 2×10^5 in 25 test sections are communicated. The rods with rod distance ratios of $P/D = 1{\cdot}025$–$2{\cdot}324$ were surrounded by hexagonal channels. The number of rods was 7, 19, 27 and 61, respectively.

The experimental and theoretical results on pressure drop coefficients in rod bundles by more than 60 authors are compiled and compared with our results. On the basis of all results the following conclusions can be drawn:

1. The pressure drop coefficients for laminar flow calculated on the basis of an earlier paper are confirmed by the experiments.
2. A critical Reynolds number could not be detected for most of the test sections.
3. With turbulent flow there is an upper limit for the pressure drop coefficient, the "equivalent" annular zone solution.
4. The pressure drop coefficient quickly rises from approximately 60 per cent of the circular tube value for closely packed rods ($P/D = 1{\cdot}0$) to the circular tube value for $P/D \approx 1{\cdot}08$. For even higher rod distance ratios, the pressure drop coefficients rise but a little to about 10% above the circular tube values at $P/D = 2{\cdot}0$.
5. The number of rods in a rod bundle has no measurable effect on the pressure drop coefficient.

NOMENCLATURE

D, rod diameter;
D_h, hydraulic diameter;
F, flow cross section;
L, characteristic length;
ΔL, measured length;
P, distance of rod centers;
Δp, pressure drop;
r_0, radius of annular zone;
r_1, radius of annular zone;
U, wetted perimeter;
u_m, flow velocity averaged over the flow cross section;
u_{max}, maximum velocity;
u^+, dimensionless velocity;
u^*, shear stress velocity;
W, wall distance (see Fig. 1b);
x, annular zone parameter;
y^+, dimensionless wall distance;
y, wall distance;
Z, number of rods;
Re, Reynolds number;
ε, depth of roughness;
λ, pressure drop coefficient;
λ_R, pressure drop coefficient of smooth circular tube;
ρ, density of flowing medium;
η, dynamic viscosity;
τ, shear stress;
τ_w, wall shear stress.

1. INTRODUCTION

DESPITE the great importance, especially in reactor technology, of the flow along parallel rods, there is still a large amount of uncertainty connected with the pressure drop coefficient for turbulent flow. This may be due to some extent to the large number of studies with partly contradictory results, partly also to a lack of systematic measurements of the pressure loss with proper variation of the geometrical parameters. Also the theoretical considerations and methods of calculation found in the literature show a large number of widely scattering results. This indicates the need for a critical survey of the data in the literature and for a comparison of these data with new measured results in order to arrive at a safe prediction of the pressure drop in rod bundles.

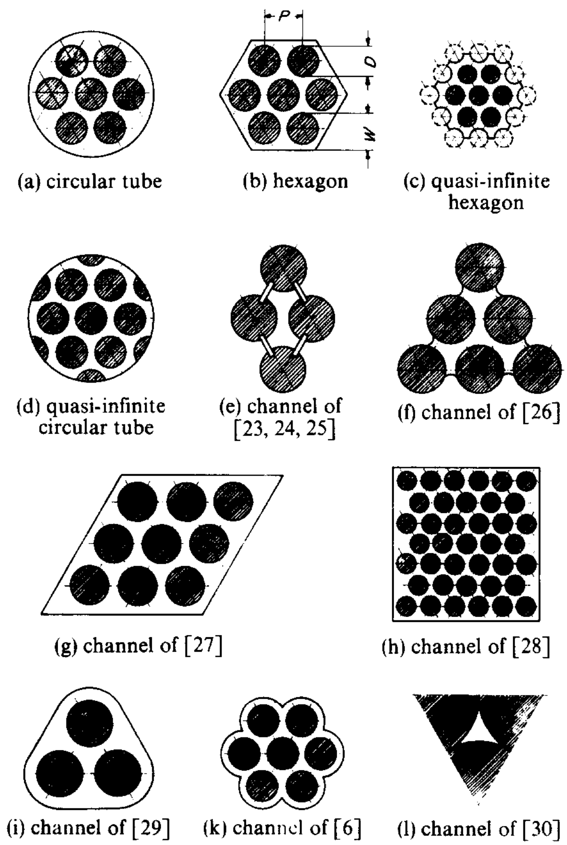

FIG. 1. Shapes of channels for rod bundles in hexagonal arrangements.

For a classification of the multitude of possible boundary conditions the scheme used in this paper will be briefly described. Only rod bundles in hexagonal arrangements will be considered; square arrangements, which behave differently with respect to the pressures drop coefficient, will be left out of consideration.

The following parameters can be distinguished:

(1) Distance ratio of the rods, P/D (Fig. 1b)
(2) Distance ratio between the rods and the channel wall W/D (Fig. 1b)

(3) Number of rods in the rod bundle Z
(4) Shape of the channel surrounding the rod bundle:
   (a) Circular tube (Fig. 1a)
   (b) Hexagonal channel (Fig. 1b)
   (c) Quasi-infinite channels; these channels are formed by closing the rod bundles on the lines of the least clearance between rods (Figs. 1c and d)
   (d) Special channels (Figs. 1e–l)

Only incompressible, isothermal, fully developed turbulent flow will be considered.

2. LITERATURE SURVEY

2.1 *Measurements of pressure drop*

A number of studies have been conducted over the past fifteen years on the pressure drop in rod bundles. Table 1 is a compilation of all studies known to the author; the main parameters of the respective studies are listed also.

In circular tubes, apart from three rods which were investigated by Presser [1], only seven rods were studied at Oak Ridge [2, 3], by Draycott and Lawther [4], Waters [5], Hoffman *et al.* [6], Presser [1] and Courtaud [7]. The rod distance ratios for these investigations ranged between $P/D = 1{\cdot}05$–$1{\cdot}536$. For larger numbers of rods, only hexagonal channels were used for hexagonal arrangements. Although there are studies of rod bundles with more than seven rods in circular tubes, these rods are arranged on concentric circles and result in a mixed hexagonal–square arrangement. These investigations will not be taken into account here. Le Tourneau *et al.* [8], Bishop *et al.* [9, 10], Galloway [11, 12], Mikhaylov *et al.* [13], and Möller *et al.* [14] investigated 19-rod bundles for $P/D = 1{\cdot}105$–$2{\cdot}055$. Sheynina [15] and Rehme [16] were concerned with 37-rod bundles for $P/D = 1{\cdot}05$–$1{\cdot}417$. Rod bundles with larger numbers of rods were studied by Wantland [17] with 102 rods and $P/D = 1{\cdot}19$, Simonek [18] with 163 rods and $P/D = 1{\cdot}4$ and Rehme [16] with 169 rods and $P/D = 1{\cdot}317$.

Investigations in quasi-infinite arrays were made by Presser [1], Subbotin *et al.* [19], Sutherland and Kays [20] and Sheynina [15] and, in quasi-infinite circular tube arrangements, by Firsova [21] and Miller *et al.* [22] for distance ratios $P/D = 1{\cdot}05$–$1{\cdot}67$. Test sections with only a small number of rods were used by Palmer and Swanson [23], Eifler and Nijsing [24], Eifler [25], Subbotin *et al.* [62], and Kjellström and Stenbäck [26]. A rhombic channel was used by Dingee and Chastain [27], a square channel by Salikov *et al.* [28]. Special channels were employed by Ibragimov *et al.* [29] and Hoffmann *et al.* [6].

In these investigations the rod distance ratios ranged between $P/D = 1{\cdot}015$–$2{\cdot}37$.

Closely packed rod bundles ($P/D = 1{\cdot}0$) were investigated by Levchenko *et al.* [30, 31], Subbotin *et al.* [19], Eifler and Nijsing [24], and Sutherland and Kays [20]. Recently published experimental results by Presser [32] are containing results of two channels with $P/D = 1{\cdot}0$ and $1{\cdot}02$, respectively, besides the results published earlier in [1].

Since it is hardly meaningful to plot all the results measured in the investigations listed above, the results of these studies have been summarized for two characteristic Reynolds numbers $Re = 10^4$ and $Re = 10^5$, respectively; care was taken to ensure that only minor extrapolations were made. The data used for this purpose are shown in Table 2. Figure 2 is a plot of all these values relative to the pressure drop coefficient of the smooth circular tube. For the circular tube, the pressure drop law recently elaborated by Maubach [33] through critical interpretation of Nikuradse's measured values [34] was employed

$$\frac{1}{\sqrt{(\lambda_R)}} = 2{\cdot}035 \log Re \sqrt{(\lambda_R)} - 0{\cdot}989. \qquad (1)$$

According to equation (1), there is a pressure drop coefficient for $Re = 10^4$ of $\lambda_R = 0{\cdot}0316$ and for $Re = 10^5$ of $\lambda_R = 0{\cdot}0182$.

As can be seen from Fig. 2, the measured values show a large amount of scatter (up to ± 40 per cent), which makes a safe prediction of the pressure drop in rod bundles from these

Table 1. List of all investigations of rod bundles in hexagonal arrangements

Author	Literature	Year	Z	P/D	W/D	D (mm)	Fig. of channel	Re-range 10^{-3}	Medium	Symbol Fig. 2
Presser	[1]	1967	3	1·1	1·06	42·0	1a	15–150	air	▽
(Oak Ridge)	[2]	1958	7	1·536	1·131	19·05	1a	15–70	air	◒
(Oak Ridge)	[2]	1958	7	1·136	1·531	19·05	1a	15–70	air	◒
(Oak Ridge)	[3]	1959	7	1·299	1·131	21·39	1a	15–60	air	◒
Draycott, Lawther	[4]	1961	7	1·125	1·125	25·4	1a	10–200	air	⊠
Draycott, Lawther	[4]	1961	7	1·219	1·219	25·4	1a	10–200	air	⊠
Waters	[5]	1963	7	1·11	1·11	19·81	1a	30–200	water	⊖
Waters	[5]	1963	7	1·2	1·2	17·88	1a	25–200	water	⊖
Hoffmann *et al.*	[6]	1966	7	1·141	1·141	25·4	1a	6–200	air	■
Presser	[1]	1967	7	1·29	1·29	24·0	1a	10–200	air	▽
Presser	[1]	1967	7	1·05	1·53	24·0	1a	10–170	air	▽
Courtaud	[7]	1966	7	1·25	1·25	25·0	1a	20–400	water	▲
Le Tourneau *et al.*	[8]	1957	19	1·12	1·12	12·7	1b	6–100	water	×
Bishop *et al.*	[9, 10]	1962	19	1·205	1·205	12·6	1b	13–70	water	+
Galloway	[11, 12]	1964	19	1·105	1·008	11·87	1b	10^{-3}–10		□
Galloway	[11, 12]	1964	19	1·266	1·082	10·36	1b	$3{\cdot}10^{-3}$–30	water +	□
Galloway	[11, 12]	1964	19	1·51	1·194	8·68	1b	10^{-2}–40	polyethyl	□
Galloway	[11, 12]	1964	19	2·055	1·444	6·38	1b	10^{-2}–50	– glycol	□
Mikhaylov *et al.*	[13]	1964	19	1·2	1·156	11·0	1b	0·7–90	air	◇
Möller *et al.*	[14]	1968	19	1·277	1·277	6·62	1b	35–230	air	▷
Sheynina	[15]	1967	37	1·05	1·02	10·0	1b	3–100	water	⦶
Sheynina	[15]	1967	37	1·4	1·42	10·0	1b	12–120	water	⦶
Rehme	[16]	1970	37	1·417	1·417	12·0	1b	6–130	water	△
Rehme	[16]	1970	37	1·275	1·275	12·0	1b	3–200	water	△
Rehme	[16]	1970	37	1·392	1·209	12·0	1b	3–100	water	△
Wantland	[17]	1956	102	1·19	1·153	4·82	1b	0·9–15	water	⬙
Simonek	[18]	1966	163	1·40	1·213	5·0	1b	150–700	air + CO_2	◓
Rehme	[16]	1970	169	1·317	1·285	6·0	1b	3–80	water	△
Presser	[1]	1967	1/7	1·05	1·05	74·0	1c	10–100	air	▽
Presser	[1]	1967	19/37	1·2	1·2	15·0	1c	5–50	air	▽
Presser	[1]	1967	19/37	1·67	1·67	15·0	1c	10–200	air	▼
Subbotin *et al.*	[19]	1960	7/19	1·13	1·13	12·0	1c	15– 70	water	●
Sheynina	[15]	1967	19/37	1·05	1·05	14·0	1c	3–120	water	⦶
Sutherland, Kays	[20]	1965	7/19	1·15	1·15	25·4	1c	8–200	air	⊘
Sutherland, Kays	[20]	1965	7/19	1·25	1·25	25·4	1c	8–200	air	⊘
Firsova	[21]	1963	7	1·2	1·2	22·0	1d	5– 20	water	-○-
Miller *et al.*	[22]	1956	37	1·46	1·46	15·88	1d	40–800	water	○
Palmer, Swanson	[23]	1961	4	1·015	—	?	1e	3– 30	air	⊗
Eifler, Nijsing	[24]	1965	4	1·021	—	40·0	1e	18– 60	water	⦸
Eifler, Nijsing	[24]	1965	4	1·059	—	40·0	1e	25–100	water	⦸
Eifler, Nijsing	[24]	1965	4	1·102	—	40·0	1e	30–100	water	⦸
Eifler, Nijsing	[24]	1965	4	1·147	—	40·0	1e	40–150	water	⦸
Eifler, Nijsing	[24]	1965	4	1·202	—	40·0	1e	40–170	water	⦸
Eifler	[25]	1968	4	1·08	—	40·0	1e	5–160	water	⦸
Kjellström, Stenbäck	[26]	1970	6	1·217	—	156·5	1f	50–200	air	◑
Dingee, Chastain	[27]	1956	9	1·12	1·12	12·7	1g	90–500	water	◨
Dingee, Chastain	[27]	1956	9	1·2	1·2	12·7	1g	90–500	water	◨
Dingee, Chastain	[27]	1956	9	1·27	1·27	12·7	1g	200–400	water	◨
Salikov *et al.*	[28]	1954	39	1·76	?	19·0	1h	6– 70	air	◪
Salikov *et al.*	[28]	1954	39	2·05	?	19·0	1h	6– 70	air	◪
Salikov *et al.*	[28]	1954	39	2·37	?	19·0	1h	6– 70	air	◪

Table 1—continued

Author	Literature	Year	Z	P/D	W/D	D (mm)	Fig. of channel	Re-range 10^{-3}	Medium	Symbol Fig. 2
Ibragimov *et al.*	[29]	1967	3	1·147	1·147	85·0	1i	18– 40	air	◧
Hoffmann *et al.*	[6]	1966	7	1·141	1·141	25·4	1k	6–150	air	■
Levchenko *et al.*	[39]	1967	3	1·0	—	205·0	1l	8–630	water	◐
Subbotin *et al.*	[19]	1960	19	1·0	—	17·6	1c	1– 15	water	●
Eifler, Nijsing	[24]	1965	4	1·0	—	40·0	1e	15– 60	water	⦸
Sutherland, Kays	[20]	1965	7	1·0	—	25·4	1c	5– 20	air	∅

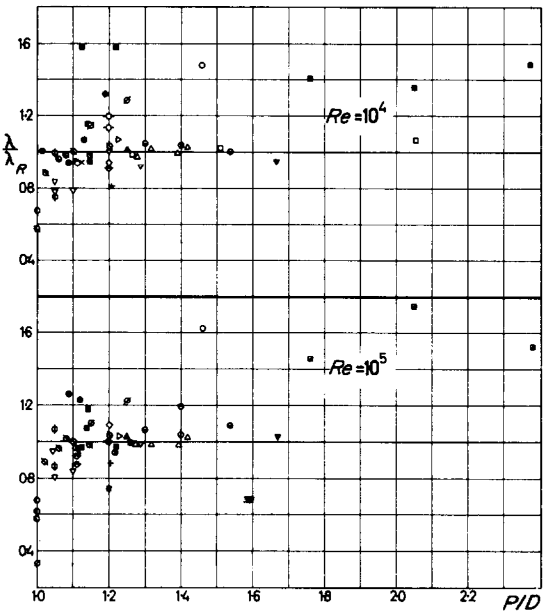

FIG. 2. Results of pressure drop measurements in rod bundles (Symbols see Table 1).

results impossible. For this reason, also earlier survey papers by Waggener [35], Sutherland [36] or Tong [37] contain no clear statements on this question.

2.2 *Calculations of pressure loss*

The methods of calculation referred to in the literature largely concern rod bundles of infinite extension, i.e. without influence of the channel wall. The fundamental theoretical work is that of Deissler and Taylor [38]. This is followed by some theoretical and empirical work and recommendations, respectively, by Russian authors on the pressure drop coefficient, for instance, by Osmachkin [39], Mikhaylov *et al.* [13], Buleev *et al.* [40], Kokorev *et al.* [41], Bogdanov [42], Inayatov [43], and Ibragimov *et al.* [44, 45]. Results of calculations of the pressure drop coefficient are indicated also by Gräber [46], Nijsing *et al.* [47], Vonka [48], and Aranovitch [49]. They were obtained in calculations of the velocity distribution in rod bundles. Subbotin *et al.* [50] also mention data on the pressure drop coefficient in rod bundles, and Presser [1] is able to describe his measured results by an empirical equation. Other work on calculation of the velocity distribution in rod bundles, e.g. by Bender and Switick [57], Rapier and Redmann [52], and Hofmann [53], unfortunately contains no explicit information on the pressure drop.

Some of the calculation methods mentioned above are contained in a paper by Minh [54]. In this paper also a formula for the pressure-drop coefficient with turbulent flow as a function of the laminar flow solution for the pressure drop developed by Gunn and Darling [55] is mentioned. The laminar flow solutions for rod bundles and subchannels of rod bundles are contained in [56–58].

Figure 3 is a presentation of all theoretical and empirical data from the literature for comparison. The calculations refer to the case of a rod bundle of infinite extension. Only the

Table 2. List of data used in Fig. 2

Author	Literature	P/D	$Re = 10^4$		$Re = 10^5$	
			λ	λ/λ_R	λ	λ/λ_R
Presser	[1]	1·1	0·0250	0·791	0·0153	0·842
Oak Ridge	[2]	1·536	0·0319	1·009	0·0199	1·095
Oak Ridge	[2]	1·136	0·0298	0·943	0·0231	1·271
Oak Ridge	[3]	1·299	0·0333	1·054	0·0195	1·072
Draycott	[4]	1·125	0·05	1·582	0·0178	0·979
Draycott	[4]	1·219	0·05	1·582	0·0178	0·979
Waters	[5]	1·11	0·0299	0·946	0·0169	0·927
Waters	[5]	1·2	0·029	0·918	0·0183	1·007
Hoffmann	[6]	1·141	0·0369	1·163	0·0215	1·183
Presser	[1]	1·29	0·0292	0·922	0·0180	0·988
Presser	[1]	1·05	0·0248	0·785	0·0147	0·809
Courtaud	[7]	1·25	0·0322	1·019	0·0188	1·034
Le Tourneau	[8]	1·12	0·03	0·949	0·0175	0·963
Bishop	[9]	1·205	0·0261	0·842	0·022	1·21
Galloway	[11]	1·105	0·03015	0·954	—	—
Galloway	[11]	1·266	0·03125	0·989	—	—
Galloway	[11]	1·51	0·0325	1·028	—	—
Galloway	[11]	2·055	0·0339	1·073	—	—
Mikhaylov	[13]	1·2	0·03	0·949	0·02	1·100
Möller	[14]	1·227	0·034	1·076	0·0188	1·034
Sheynina	[15]	1·05	0·024	0·759	0·0158	0·869
Sheynina	[15]	1·4	0·033	1·044	0·019	1·045
Rehme	[16]	1·417	0·0325	1·028	0·0187	1·029
Rehme	[16]	1·275	0·031	0·981	0·018	0·99
Rehme	[16]	1·392	0·0315	0·997	0·018	0·99
Wantland	[17]	1·19	0·0418	1·323	—	—
Simonek	[18]	1·4	—	—	0·0218	1·196
Rehme	[16]	1·317	0·0325	1·028	0·018	0·99
Presser	[1]	1·05	0·0266	0·842	0·0173	0·953
Presser	[1]	1·2	0·0320	1·011	0·0198	1·089
Presser	[1]	1·67	0·03	0·949	0·0188	1·032
Subbotin	[19]	1·13	0·034	1·076	0·0225	1·238
Sheynina	[15]	1·05	0·0316	1·00	0·0195	1·073
Sutherland	[20]	1·15	0·0364	1·152	0·0202	1·109
Sutherland	[20]	1·25	0·0407	1·289	0·0224	1·234
Firsova	[21]	1·2	0·038	1·203	—	—
Miller	[22]	1·46	0·0469	1·484	0·0296	1·628
Palmer	[23]	1·015	0·032	1·013	—	—
Eifler	[24]	1·021	—	0·89	—	0·89
Eifler	[24]	1·059	—	0·97	—	0·97
Eifler	[24]	1·102	—	1·01	—	1·01
Eifler	[24]	1·147	—	0·99	—	0·99
Eifler	[24]	1·202	—	1·04	—	1·04
Eifler	[25]	1·08	—	0·99	—	1·025
Kjellström	[26]	1·217	—	—	0·0172	0·946
Dingee	[27]	1·12	—	—	0·0175	0·963
Dingee	[27]	1·2	—	—	0·0136	0·745
Dingee	[27]	1·27	—	—	0·0182	1·001
Salikov	[28]	1·76	0·0445	1·408	0·0266	1·463
Salikov	[28]	2·05	0·043	1·361	0·032	1·760
Salikov	[28]	2·37	0·047	1·487	0·0278	1·529
Ibragimov	[29]	1·147	—	0·948	—	—
Hoffmann	[6]	1·141	—	—	0·0198	1·088
Levchenko	[30]	1·0	0·0215	0·68	0·0113	0·622
Subbotin	[19]	1·0	0·02	0·633	—	—
Eifler	[24]	1·0	—	0·58	—	0·58
Sutherland	[20]	1·0	0·0106	0·335	—	—

curves by Mikhaylov, Bogdanov and Presser apply to rod bundles; they are empirical formulae obtained from measured results. There is relatively good agreement for rod distance ratios $P/D < 1{\cdot}1$. For higher rod distance ratios, there is a wide range of results. Figure 3 also shows the years of publication of the respective papers.

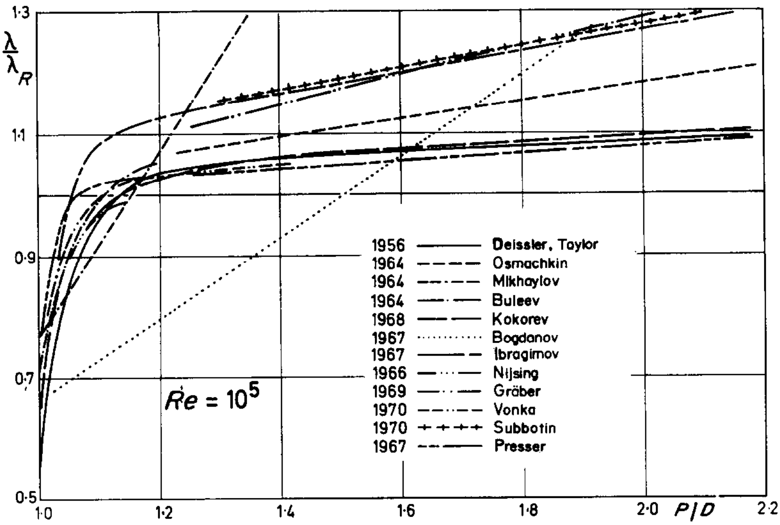

FIG. 3. Pressure drop coefficients in rod bundles; recommendations and calculations.

From these years it is evident that the calculated values do not converge against the probable value over the years. The uncertainty with respect to the pressure drop coefficient thus is just as high in various methods of calculation as it is with the measured values.

3. EXPERIMENTS

For the reasons outlined above, the pressure drop in rod bundles in a hexagonal arrangement was systematically investigated experimentally. In order to have a safe basis for comparison among the experiments, the following restrictions of the possible geometrical parameters were made.

3.1 *Experimental conditions*

The rod bundles investigated had

(a) the clearance between the outer row of rods and the channel wall equal to the clearance between the rods,

(b) a hexagonal channel as the outer boundary.

The parameters varied were

(a) the rod distance ratio

(b) the number of rods in a rod bundle.

The experiments were performed in a hydraulic test loop with a flow rate of $0{\cdot}1\ m^3/s$ with a differential pressure at the test section of 1·3 MPa. The rods made of stainless steel of $D = 12$ mm dia. were supported by perforated plates at the inlet and outlet and had been inserted into hexagonal channels. The channels were those described in detail in [59]; they were cast around hexagonal cores with synthetic resin. The test sections had a length of $L = 1500$ mm, the length of the bundle being 1000 mm. The entire test facility is described in detail in [59, 60].

Small flow rates ($2{\cdot}5 \times 10^{-5}$ to 5×10^{-3} m^3/s) were determined by turbine flowmeters, larger ones by means of an inductive flowmeter. The differential pressures were measured with U-tube pressure gauges; manometer fluids were dichlorethane, carbon tetrachloride, bromoform and mercury relative to water, depending upon the size of the differential pressure.

Pressure drops were measured in a total of 25 test sections. The dimensions and geometrical parameters of the rod bundles are listed in Table 3. It is seen that the condition that the clearance between the outer row of rods and the wall should be equal to the clearance between rods ($P/D = W/D$) is fulfilled very well, aside from the test sections at small clearances between rods ($P/D < 1{\cdot}1$). It was difficult in these test sections to maintain the small clearances relative to the wall with that accuracy because of the tolerances in the width across flats of the channel and the arrangement of tne bundles.

Table 3. Data of rod bundles under study

No.	Number of rods, Z	Rod clearance, a	Rod distance ratio, P/D	Width over the flats of hexagon SW (mm)	Wall distance ratio, W/D	Hydraulic diameter, D_h (mm)	Hydraulic diameter, D_∞ (mm)
1	61	0·30	1·025	98·67	1·060	2·322	1·902
2	37	0·89	1·075	81·27	1·095	3·665	3·291
3	61	1·00	1·084	103·93	1·076	3·693	3·548
4	7	1·50	1·125	38·80	1·142	5·143	4·747
5	19	1·51	1·126	62·19	1·142	5·157	4·776
6	61	1·48	1·124	108·33	1·122	4·88	4·717
7	7	2·77	1·231	43·61	1·251	8·249	8·051
8	19	2·78	1·231	69·23	1·252	8·375	8·051
9	37	2·82	1·235	94·98	1·250	8·420	8·182
10	7	3·35	1·279	45·22	1·276	9·314	9·645
11	19	3·32	1·276	72·44	1·308	9·907	9·544
12	37	3·29	1·275	98·67	1·300	9·783	9·510
13	7	4·15	1·346	48·19	1·342	11·33	11.97
14	19	4·13	1·344	76·05	1·341	11·68	11·90
15	37	4·14	1·345	103·93	1·335	11·78	11·94
16	7	5·05	1·421	51·66	1·422	13·73	14·72
17	19	5·05	1·421	81·27	1·425	14·33	14·72
18	37	5·04	1·420	110·64	1·420	14·43	14·68
19	61	5·00	1·416	139·60	1·411	14·34	14·53
20	19	9·09	1·757	103·93	1·786	26·78	28·85
21	37	9·07	1·756	139·60	1·754	27·03	28·80
22	7	10·40	1·867	72·44	1·902	29·16	34·12
23	19	10·38	1·865	110·64	1·880	30·75	34·02
24	7	15·88	2·324	94·98	2·445	47·47	59·47
25	19	15·78	2·315	139·60	2·306	49·10	58·91

3.2 *Method of evaluation*

For calculation of the pressure drop coefficient λ, differential pressures Δp were measured over a length ΔL containing no spacers.

In order to ensure hydrodynamic development of the flow the measurement section normally was 30 D_h downstream of the inlet. Only for rod distance ratios $P/D > 1{\cdot}5$, this section was less than 30 D_h, but at least 15 D_h. Undisturbed startup lengths of this magnitude are probably sufficient for measurements of the pressure drop.

The pressure drop coefficient λ is defined as

$$\lambda = \frac{\Delta p/\Delta L}{(\rho/2)\, u_m^2\, (1/D_h)} \quad (2)$$

with u_m as the mean flow velocity averaged over the entire flow cross section F, ρ as the density of the flow medium (water) determined through a temperature measurement, and D_h as the hydraulic diameter defined with the total wetted perimeter U (including the channel wall) as

$$D_h = \frac{4F}{U}. \quad (3)$$

The pressure drop coefficients determined for all the test sections are listed in [68] together with the respective Reynolds numbers. The Reynolds number is defined with η as the dynamic viscosity of the flow medium determined through a temperature-measurement as

$$Re = \frac{\rho u_m D_h}{\eta}. \quad (4)$$

4. RESULTS

Figure 4 shows all the measured results as pressure drop coefficients over the Reynolds numbers. For comparison in the turbulent flow region the curve of the pressure drop coefficient for the smooth circular tube according to equation (1) has been included. The line shown for laminar flow has been calculated from theoretical data contained in an earlier paper by the author [58].

As is evident from the figures, the experimental investigation had the following results:

(a) No effect of the number of rods Z on the pressure drop coefficient can be found. If the number of rods has an influence on the pressure drop coefficient, it is within the inaccuracy of measurement of the results. The main reason of this result is probably the uniform flow distribution over the rod bundles in all cases investigated. If the same pressure drop coefficient is assumed in a first approximation for all subchannels of a rod bundle, this results in a uniform flow distribution, provided the hydraulic diameters of the subchannels are equal. This was more or less the case in the investigations conducted. This fact can be seen from Table 3 by comparing the hydraulic diameters D_h of the actual arrangements with those of an infinite rod bundle. In general, the hydraulic diameters differ by less than 8 per cent.

(b) The influence of the rod distance ratio P/D on the pressure drop coefficient is very weak for rod distance ratios $P/D > 1{\cdot}1$. The pressure drop coefficients increase from the smooth circular tube value for $P/D \approx 1{\cdot}1$ to only about 10 per cent above the values of circular tubes at $P/D \approx 2$. This result contradicts many measured results mentioned in the literature. For $P/D < 1{\cdot}1$, the pressure drop coefficient decreases rapidly to approximately 60 per cent of the value for circular tubes for $P/D = 1{\cdot}0$, as is evident from the literature [19, 24, 30].

(c) No influence of surface roughness on the pressure drop coefficient can be ascertained. The measured depth of roughness of the surfaces of the rods was $\varepsilon = 2 \times 10^{-6}$ m on the average. The depth of roughness of the channel surfaces was not measured. However, the channel walls were very smooth as a result of their being made of synthetic resin.

(d) For low Reynolds numbers in the laminar flow region there is very good agreement with the calculated values; the number of measured points in the laminar region is very small, however, because of the very low differential pressures.

(e) A sudden change from laminar to turbulent flow cannot be detected for most of the rod bundles. There is an area of transition in which the pressure drop coefficients gradually change from a more laminar behavior (Re^{-1}) to a turbulent ($Re^{-0{\cdot}2}$) behavior. This is understandable, if one considers that there is still delayed flow in the close gaps between the rods although the main flow is already turbulent. Of course, this is no longer the case with large clearances between rods, and this is where a change is noticed. The Reynolds number at which this change occurs is shifted towards higher values relative to the circular tube. This may be explained by the definition of the hydraulic diameter which is known to increase in square proportion with the rod distance ratio and thus influences the Reynolds number.

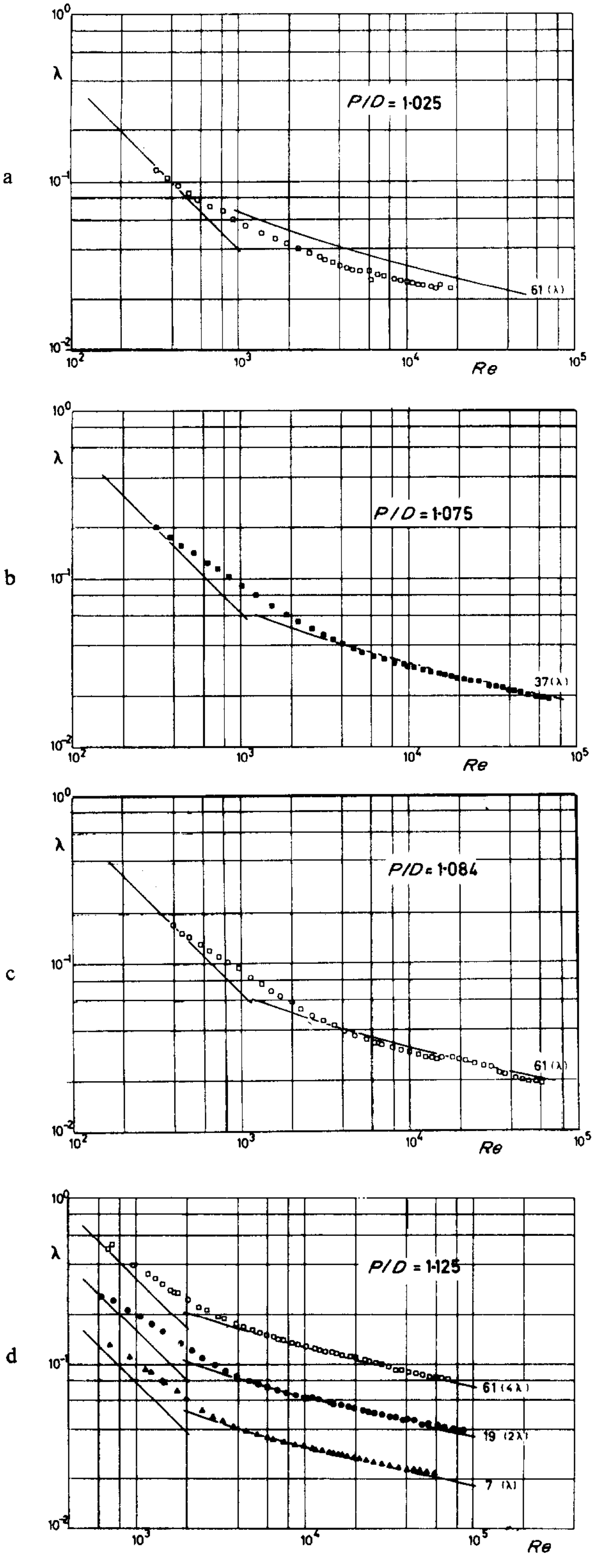
a
P/D = 1·025
61 (λ)
b
P/D = 1·075
37 (λ)
c
P/D = 1·084
61 (λ)
d
P/D = 1·125
61 (4λ)
19 (2λ)
7 (λ)
λ
Re

FIG. 4(1).

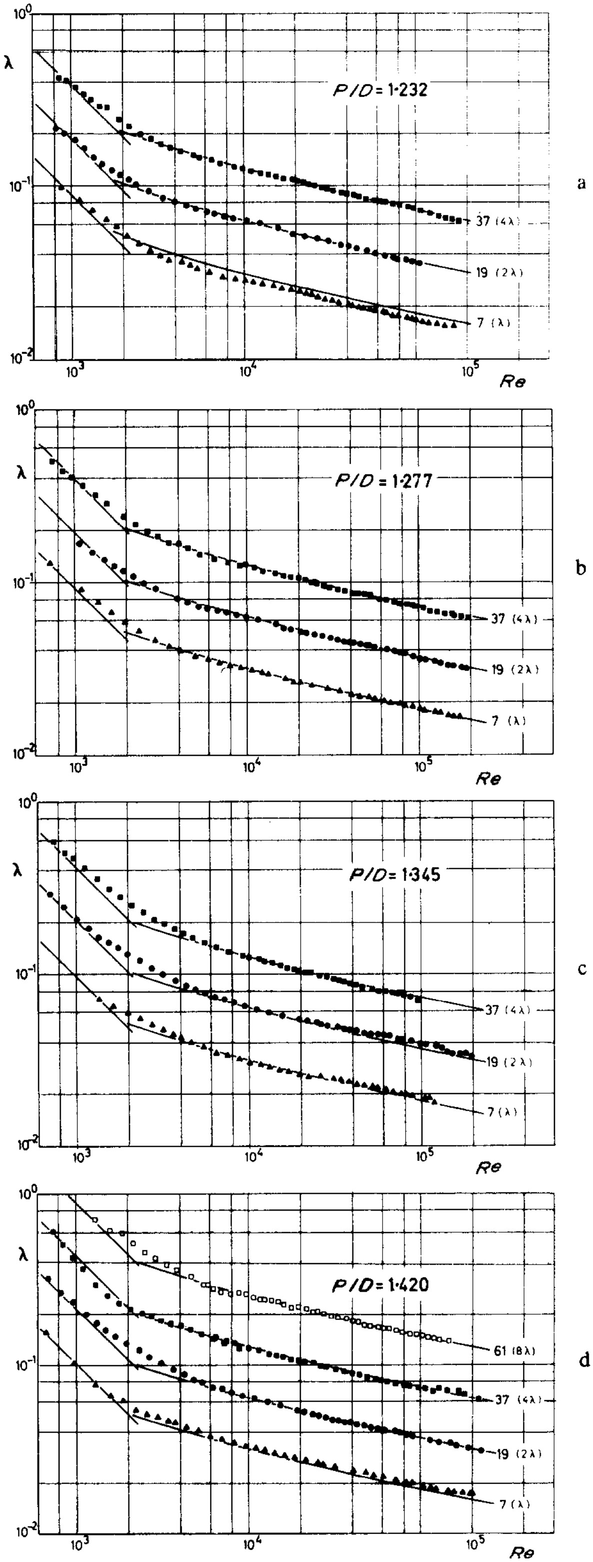
a
P/D = 1·232
37 (4λ)
19 (2λ)
7 (λ)
b
P/D = 1·277
37 (4λ)
19 (2λ)
7 (λ)
c
P/D = 1·345
37 (4λ)
19 (2λ)
7 (λ)
d
P/D = 1·420
61 (8λ)
37 (4λ)
19 (2λ)
7 (λ)
λ
Re

FIG. 4(2).

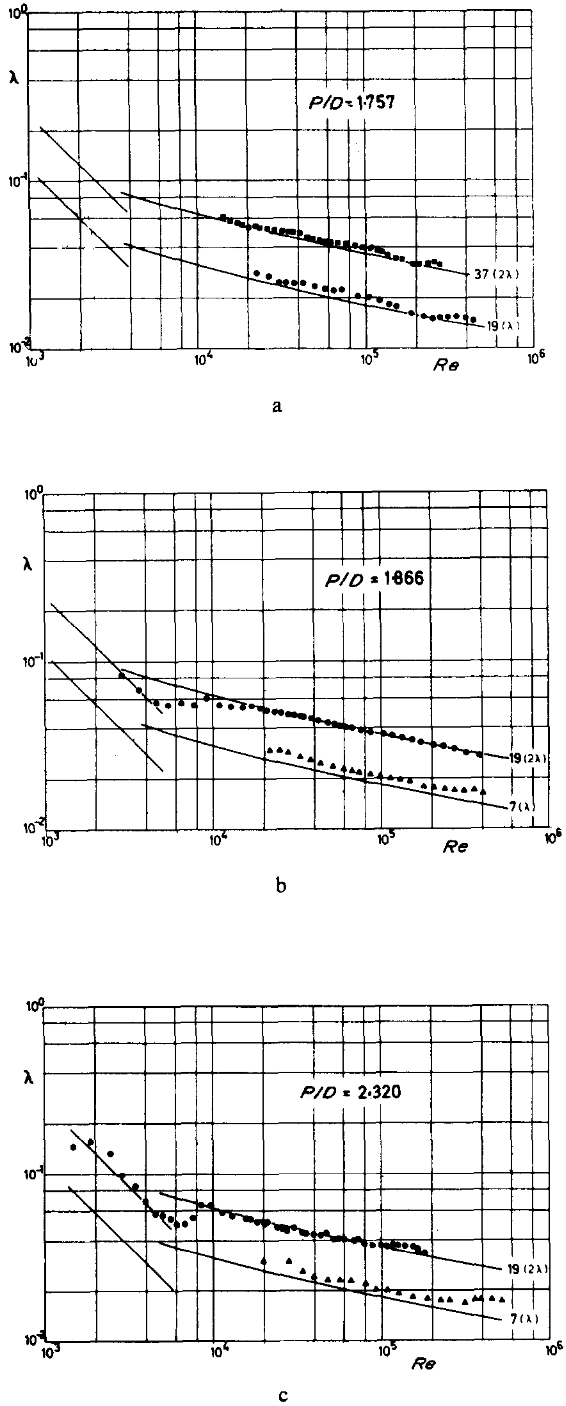

FIG. 4. Pressure drop coefficients as a function of the Reynolds number.

5. COMPARISON OF DATA IN THE LITERATURE WITH MEASURED RESULTS

5.1 *Comparison with data measured by other authors*

In order to arrive at safe general statements about the pressure drop coefficient in rod bundles, Fig. 5 shows a plot of all the measured results for rod bundles in a hexagonal arrangement in hexagonal channels over the rod distance ratios (values from the literature and measurements by the author) for $Re = 10^4$ and $Re = 10^5$, respectively, referred to the pressure drop coefficient of the circular tube. The data used from the measurements by the author are compiled in Table 4 and have been plotted in Fig. 5 by different symbols depending upon the number of rods. For comparison, the curve of the pressure drop coefficient of the "equivalent" annular zone has been included also. The "equivalent" annular zone is produced if the hexagonal elementary cell around each rod in an infinite rod bundle is replaced by the annular zone of the same area (cf. Fig. 6). If the universal velocity profile for circular tubes [34] by Nikuradse,

$$u^+ = 2{\cdot}5 \ln y^+ + 5{\cdot}5 \tag{5}$$

with $u^+ = u/u^*$ as the dimensionless flow velocity and $y^+ = \rho y u^*/\eta$ as the dimensionless distance from the wall with $u^* = \sqrt{(\tau_w/\rho)}$ as the friction velocity is assumed to be valid also for the annular zone, the result for the annular zone according to Maubach [33] is:

$$\sqrt{\left(\frac{8}{\lambda}\right)} = 2{\cdot}5 \ln \frac{\rho L u^*}{\eta} + 5{\cdot}5 - \frac{3{\cdot}75 \times 1{\cdot}0576 + 1{\cdot}25x}{1 + x} \tag{6}$$

where $x = r_0/r_1$ (see Fig. 6) is the parameter of the annular zone $L = r_0 - r_1$ the width of the annular zone and

$$D_h = \frac{r_0^2 - r_1^2}{2r_1}$$

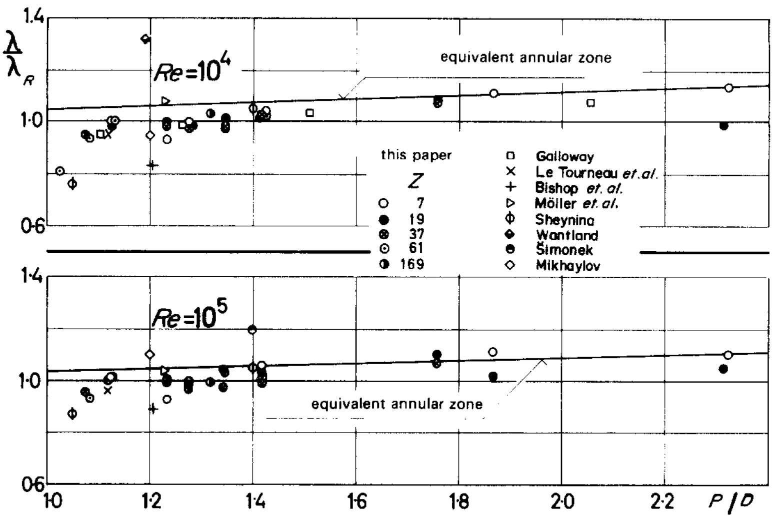

FIG. 5. Results of measured pressure drop coefficients for rod bundles in hexagonal channels.

Table 4. List of data used in Fig. 10

Test section No.	Z	P/D	$Re = 10^4$		$Re = 10^5$	
			λ	λ/λ_R	λ	λ/λ_R
1	61	1·025	0·0254	0·804	—	—
2	37	1·075	0·0300	0·949	0·0174	0·957
3	61	1·084	0·0296	0·937	0·0169	0·930
4	7	1·125	0·0317	1·003	0·0184	1·012
5	19	1·126	0·0310	0·981	0·0184	1·012
6	61	1·124	0·0318	1·006	0·0184	1·011
7	7	1·231	0·0294	0·930	0·0168	0·942
8	19	1·231	0·0315	0·997	0·0180	0·990
9	37	1·235	0·031	0·981	0·0183	1·004
10	7	1·279	0·0315	0·997	0·0183	1·007
11	19	1·276	0·0314	0·994	0·0179	0·985
12	37	1·275	0·0308	0·973	0·0178	0·976
13	7	1·346	0·0306	0·968	0·0189	1·040
14	19	1·344	0·0320	1·013	0·019	1·045
15	37	1·345	0·0310	0·981	0·0178	0·976
16	7	1·421	0·0325	1·028	0·0192	1·056
17	19	1·421	0·0320	1·013	0·01865	1·026
18	37	1·420	0·0315	0·997	0·0182	1·001
19	61	1·416	0·0320	1·013	0·0185	1·018
20	19	1·757	0·0342	1·082	0·020	1·100
21	37	1·756	0·034	1·076	0·0195	1·073
22	7	1·867	0·0352	1·114	0·0202	1·111
23	19	1·865	(0·028)	(0·886)	0·0185	1·018
24	7	2·324	0·0358	1·133	0·02	1·100
25	19	2·315	0·031	0·981	0·019	1·045

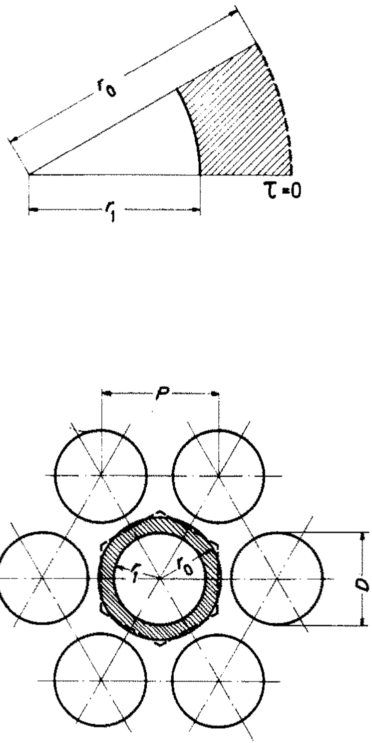

FIG. 6. "Equivalent" annular zone.

its hydraulic diameter. This supplies

$$\sqrt{\left(\frac{8}{\lambda}\right)} = 2{\cdot}5 \ln Re \sqrt{\left(\frac{\lambda}{8}\right)} + 5{\cdot}5 - \frac{3{\cdot}966 + 1{\cdot}25x}{1 + x} - 2{\cdot}5 \ln 2(1 + x). \quad (7)$$

For the "equivalent" annular zone of hexagonally arranged rod bundles, x turns out to be

$$x = \sqrt{\left(\frac{2\sqrt{(3)}}{\pi}\right)}\frac{P}{D}. \quad (8)$$

As an approximation, the pressure drop coefficient from the annular zone solution referred to the circular tube value λ_R from equation (1) for rod bundles of infinite extension turns out to be

$$\text{for } Re = 10^4: \lambda/\lambda_R = 1{\cdot}045 + 0{\cdot}071\,(P/D - 1) \quad (9)$$

$$\text{for } Re = 10^5: \lambda/\lambda_R = 1{\cdot}036 + 0{\cdot}054\,(P/D - 1) \quad (10)$$

The "equivalent" annular zone is a good approximation of rod bundles with large rod distance ratios ($P/D > 1{\cdot}2$) for which the wall shear stress is relatively constant around the perimeter of the rod. For smaller rod distance ratios, the pressure drop coefficients are below those of the annular zone. This results from the non-uniform velocity and wall shear stress distributions and from the fact that the hydraulic diameter does not take into account these irregularities. It is seen from Fig. 5 that almost all the measured values are below the line for the "equivalent" annular zone. The same behavior was found also with laminar flow in rod bundles [58]. In rod bundles, the channel wall has the effect of causing the pressure drop coefficients always to be below the values for infinite rod bundles and thus below the values of the "equivalent" annular zone.

A maximum of the pressure drop coefficient is obtained for uniform flow distribution through the rod bundle [1, 7, 29] i.e. for nearly identical hydraulic diameters of the subchannels (cf. 4a), which condition was more or less met in the studies. For closer or wider clearances from the walls or other arrangements [61], more or less non-uniform flow distributions will result and, hence, there will always be lower pressure drop coefficients. This fact is confirmed in investigations of laminar flow [7, 58].

Since the influence of the channel wall must result in a similar effect in rod bundles not surrounded by hexagonal channels, it can be concluded that the values for the "equivalent" annular zone represent the upper limit of the pressure drop coefficient also for these arrangements. Recently published measurements of Subbotin *et al.* [62] confirm this statement. Since the pressure drop coefficients according to the "equivalent" annular zone solution rise with the rod distance ratio, there is no constant upper value of the pressure drop coefficient for rod bundles with high distance ratios, as supposed by Presser [32]. It is possible to determine analogous geometrical effects on the pressure drop coefficient with laminar and turbulent flow. But from the fact that there is no upper limit for the pressure drop coefficient of rod bundles with high distance ratios with laminar flow one has to draw the conclusion that there is no upper limit even with turbulent flow, and not vice versa. For laminar flow, the results by Sparrow and Loeffler [56] which cannot be called in question, the analytically obtained "equivalent" annular zone solution, and earlier results of the author [58] confirm this statement. The difference between the experimental results for laminar flow obtained by Presser [32] and the theoretical solutions could come either by the influence of the channel walls not taken into account by Presser or by experimental error.

Considering the annular zone solution as the upper limit the measured results listed in Tables 1 and 2, respectively, which give higher values than the annular zone solution, must be due to other reasons, such as

(a) influence of surface roughnesses
(b) inaccurate knowledge of geometrical parameters (F, U)
(c) increase in pressure drop by inlet and outlet losses
(d) increase in pressure drop by spacers
(e) measurement with the flow not yet fully developed
(f) measurements errors and inaccuracies because some of the pressure drop results were obtained as by-products of heat transfer measurements.

It is a well-known fact that the hydraulic diameter does not fit the role of the characteristic length converting the pressure drop coefficients to the circular tube values for all geometries. The higher or lower values of the pressure drop coefficients depending on the distance between the wall and the rods for rod bundles at the same hydraulic diameter demonstrate this fact rather clearly.

Defining a characteristic length in a different way, so that all rod bundles obey only one pressure drop law, appears to be impossible, even in view of the laminar solutions [58].

For this reason, the attempt made by Subbotin [19], used also in [21] and recently by Presser [32] to introduce the diameter of the inscribed circle, instead of the hydraulic diameter as the characteristic length, must be regarded as a failure. The pressure drop coefficient defined in this way decreases below the value of the circular tube for large rod distance ratios (at $P/D = 2$ to roughly 40 per cent of the value for the circular tube) and thus cannot be used to generate the circular tube values for all rod distance ratios. However, already Subbotin indicated the possibility of a fortuitous agreement of the pressure drop coefficients between the circular tube and the rod bundle when using the diameter of the inscribed circle as the characteristic length.

5.2 *Comparison with theoretical and empirical relations*

Some remarks should be made about the theoretical and empirical recommendations for the pressure drop coefficient of rod bundles of infinite extension:

(a) The empirical relations suggested by Mikhaylov *et al.* [13] and Bogdanov [42] are too simple because a linear dependence of the pressure drop coefficient on the rod distance ratio is assumed, which makes them too inaccurate.

(b) The special method of Osmachkin [39] of obtaining the characteristic length from the laminar solution by comparison with the laminar value for circular tubes and using this length in turbulent flows in the circular tube laws, supplies values which are too high. Too high values are also the results using the method of Gunn and Darling [55] based on the laminar solutions.

(c) Calculations based on velocity laws other than those indicated by Nikuradse [33] and Reichardt [63], respectively, also result in pressure drop coefficients which are too high. Experimental investigations of the velocity distribution in rod bundles always show excellent agreement with these laws [24–26, 29–31, 62]. Pressure drop coefficients which are too high are furnished also by the calculations according to

Subbotin *et al.* [50] on the basis of a method for annuli indicated by Rothfus *et al.* [64] through modification of the coordinate normal to the wall, in which the velocity distribution of the tube is obtained under the wrong assumption that the line of zero shear stress is in the same position for both laminar and turbulent flows and, at the same time, is on the line of maximum velocity. Also calculations by Gräber [46], who gives a formula for the eddy diffusivity as a function of the known shear stress distribution and then calculates the velocity field, and calculations carried out with the velocity profiles indicated by Eifler [65], result in pressure drop coefficients which are too high.

The velocity profiles developed by Eifler as well as the calculations by Gräber are strongly based on the erroneous interpretations of the measurements of Brighton and Yones [66] for annuli with extreme radius ratios for which a coincidence of the lines of maximum velocity u_{max} and zero shear stress $\tau = 0$ were assumed. This coincidence can no longer be assumed in the light of more recent knowledge [67].

(d) Calculations by Ibragimov *et al.* [44] with empirical factors for the curvature of the wall and the irregularity of the flow cross section also result in pressure drop coefficients which are too high.

Hence, the useful possibilities of calculations found on the basis of the new experimental findings are these:

(A) The cumbersome calculations due to the basic work by Deissler and Taylor [38]; the authors use Deissler's profile which differs but slightly from Nikuradse's. The same profile is used also by Aranovitch [49]. Kokorev *et al.* [62] use Reichardt's profile. The results of these calculations are in very good agreement with the annular zone solutions according to Maubach [33] for $P/D > 1{\cdot}4$ and appear to give the best pressure coefficients also for $P/D < 1{\cdot}4$.

(B) An empirical relation which may be regarded as a good approximation for the upper limit of the pressure drop coefficient in rod bundles is probably the formula by Presser [1].

6. CONCLUSIONS

From these considerations and from the new measured results communicated in this paper it can be concluded that the pressure drop coefficient for isothermal, incompressible, fully developed turbulent flow in rod bundles does not exceed an upper limit, i.e. the annular zone solution. For rod bundles occurring in practice with channel walls, the pressure drop coefficient is lower than the annular zone solution mentioned above, depending upon the type and position of the channel walls. For rod bundles with uniform flow distribution commonly used, the pressure drop coefficient is close to the upper limit; the more irregular the flow, the lower the pressure drop coefficient will be. This proves that the numerous pressure drop coefficients mentioned in the literature, some of which are very much on the high side, do not correspond to the real conditions of flow in rod bundles with smooth walls. For the pressure drop coefficient there is a rapid increase from 60 per cent of the circular tube value at a rod distance ratio of $P/D = 1$ to approximately 100 per cent at $P/D \approx 1{\cdot}08$. For higher rod distance ratios, the pressure drop coefficient increases to only some 110 per cent of the tube value for $P/D = 2{\cdot}0$.

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CHUTE DE PRESSION DANS LES FAISCEAUX DE TIGES A ARRANGEMENTS HEXAGONAUX

Résumé—Des études systématiques ont été conduites sur la chute de pression pour un écoulement turbulent incompressible, isotherme, pleinement développé dans des faisceaux avec arrangement hexagonal des tiges. On donne les résultats des mesures de la chute de pression dans un domaine de nombre de Reynolds $Re = 6\ 10^2$ à $2\ 10^5$ pour 25 sections. Les tiges sont disposées selon le rapport des distances $P/D = 1{,}025$ à 2,324 dans des canaux hexagonaux. Le nombre de tiges est respectivement égal à 7, 19, 37 et 61.

Les résultats expérimentaux et théoriques sur les coefficients de chute de pression dans les faisceaux de tiges obtenus par plus de 60 auteurs sont rassemblés et comparés avec nos résultats. Sur la base de tous ces résultats on peut tirer les conclusions suivantes:

1—Les coefficients de chute de pression pour l'écoulement laminaire calculés à partir d'un précédent article sont confirmés par les expériences.
2—On ne peut pas détecter un nombre de Reynolds critique pour la plupart des sections étudiées.
3—Pour l'écoulement turbulent il existe une limite supérieure du coefficient de chute de pression, la solution de l'anneau "équivalent".
4—Le coefficient de perte de pression en canal circulaire croît rapidement d'environ 60 pour cent depuis sa valeur pour un faisceau de tiges serrées ($P/D = 1$) à sa valeur pour $P/D \simeq 1{,}08$. Avec des rapports d'écartement de tiges plus élevés, le coefficient de chute de pression augmente, mais légèrement d'environ 10 pour cent à $P/D = 2{,}0$.
5—Le nombre de tiges dans un faisceau n'a pas d'effet mesurable sur le coefficient de chute de pression.

DRUCKABFALL IN STABBUNDELN BEI HEXAGONALER ANORDNUNG

Zusammenfassung—Der Druckabfall wurde systematisch untersucht für inkompressible, isotherme, voll entwickelte turbulente Strömungen in Stabbündeln mit hexagonaler Anordnung der Stäbe. Die Ergebnisse der Messungen des Druckabfalls werden mitgeteilt für einen Bereich der Reynolds-Zahlen von $Re = 6 \cdot 10^2$ bis $2 \cdot 10^5$ in 25 Testabschnitten. Die Stäbe mit Abmessungsverhältnissen $P/D = 1{,}025$–$2{,}324$ werden von hexagonalen Kanälen umgeben. Die Anzahl der Stäbe betrug 7, 19, 37 und 61.

Die experimentellen und theoretischen Ergebnisse von mehr als 60 Autoren über Druckabfallkoeffizienten in Stabbündeln werden gesammelt und mit unseren Ergebnissen verglichen. Auf Grund all dieser Ergebnisse kann man folgende Schlüsse ziehen:

(1) Die Druckabfallkoeffizienten für laminare Strömung, berechnet nach einer früheren Veröffentlichung, werden durch die Experimente bestätigt.
(2) Eine kritische Reynolds-Zahl konnte bei den meisten Testabschnitten nicht entdeckt werden.
(3) Bei turbulenter Strömung gibt es eine obere Grenze für den Druckabfallkoeffizienten, die "aquivalente" Ringraumlösung.
(4) Der Druckabfallkoeffizient steigt schnell an von etwa 60% des Wertes für Kreisrohre und dichtgepackte Stäbe ($P/D = 1.0$) auf den Werte für Kreisrohre bei $P/D \approx 1{,}08$. Für noch grössere Stababstandsverhältnisse steigt der Druckabfallkoeffizient nur wenig, bis ca. 10% über den Wert von Kreisrohren bei $P/D = 2{,}0$.
(5) Die Zahl der Stäbe in einem Stabbündel hat keinen messbaren Einfluss auf den Druckabfallkoeffizienten.

СОЗДАНИЕ ПЕРЕПАДОВ ДАВЛЕНИЯ ПУЧКАМИ СТЕРЖНЕЙ В ГЕКСАГОНАЛЬНОМ РАСПОЛОЖЕНИИ

Аннотация—Проведены систематические исследования перепада давления при несжимаемом, изотермическом, полностью развитом турбулентном течении в пучках стержней с гексагональным расположением стержней. Представлены результаты измерений перепада давлений в диапазоне чисел Рейнольдса $Re = 6\times10^2$–2×10^5 для 25 исследованных поперечных сечений. Стержни с отношениями шага к диаметру $P/D = 1{,}025$–$2{,}324$ находились в гексагональных каналах. Число стержней соответственно равнялось 7, 19, 37 и 61.

Собраны экспериментальные и теоретические значения коэффициентов перепада давления в пучках стержней более чем 60 авторов и проведено сравнение с нашими результатами. На основании сравнения можно сделать следующие выводы:

1. Коэффициенты перепада давления для ламинарного потока, рассчитанные на основе опубликованной ранее работы, подтверждаются экспериментально.

2. Для большинства из исследованных поперечных сечений не обнаружено критического значения критерия Рейнольдса.