REPLY TO THE COMMENTS OF M. A. GOTOVSKII AND E. V. FIRSOVA

E. K. Kalinin and G. A. Dreitser

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The formula presented in [1], formula (5), for calculating the hydraulic resistance of longitudinally washed staggered tube bundles is empirical, and the recommended range of Re of its application is that of the corresponding experimental investigations. Analysis of the test data shows that the hydraulic resistance of the longitudinally washed bundles with small numbers of tubes depends strongly on the shape of the sheath. In the generalization, therefore, we used data for bundles with a large number of tubes. In all the papers, in [2] for s/d = 1.13, in [3] for s/d = 1.12, and in [4] for s/d = 1.46 (besides [2] for s/d = 1), we determined the dependence of the resistance coefficient ζ on Re for the turbulent region to be as the power −0.2. Incidentally, a similar dependence of ζ on Re was obtained in a work of one of the authors of the comments [5]. An analogous dependence of ζ on Re was observed also in [6] for a staggered bundle with s/d = 1.28, and in [7]. This circumstance was naturally taken into account in deriving the generalized formula, in spite of the fact that in our experiments [1], the dependence of ζ on Re declines somewhat with increase of Re.

The authors of the comments attempt incorrectly to explain the dependence of ζ on Re obtained in [1] for a bundle with s/d = 1.2 by the influence of roughness. The surface of the experimental tubes and of the body used in [1] was polished, and roughness had no influence on the results obtained. In the theoretical paper [8] the dependence of ζ on Re which was obtained also declines with increase of Re. The fact that the resistance data of [1] lie somewhat below those of [2], for s/d = 1.13, may evidently be explained by the influence of the shape of the body. An important point is that the data on ζ for bundles with plane body surfaces are located in general below the corresponding data for bundles with figured expellers. Thus, for example, the data of [2] for a bundle with s/d = 1.13 with expellers lie above those of [3] for a bundle with a close pitch s/d = 1.12 without expellers. The results in papers [1] and [6] for bundles located in a sheath with plane surfaces fall below the data for bundles with figured expellers (when corrected for the dependence of ζ on s/d).

The critique by the authors of the comments regarding the test data of [4] on hydraulic resistance is not convincing. A determination was made in [4] of the dependence of ζ on Re over a wide range of Re number, and the mean scatter of the test points about the average curve was of the order of 7%, with a maximum up to 20%, i.e., the scatter is usual for similar investigations. Excluding certain points, the scatter is, for example, of the same order as in the paper of one of the authors of the comments [5]. The results of reference [4] are used in a number of monographs, for example [9], with a recommendation for practical calculations.

The calculation formula (5) obtained in [1] generalizes the available experimental data for bundles with a large number of tubes, the maximum scatter of the test points being of the order of 10–15%. The data of [1, 2] for s/d = 1 are located below (formula (5) in [1]), and the data of [2] for s/d = 1.13 and the data of [3, 4] are above it (the results of [2] for s/d = 1.13 in fact fall somewhat higher than shown in Fig. 2 of [1]). The results of earlier work [6] for s/d = 1.28 are also in satisfactory agreement with the formula obtained.

Reference [10], cited by the authors of the comments in criticizing the generalized formula obtained in [1], refers to bundles with large relative pitch (s/d = 1.76, 2.04, 2.37) and the work was done with comparatively large values of Re (up to 50 000). These results are therefore not generalized by the formula obtained in [1], which relates to $1 \le s/d \le 1.46$ and larger Re values (at large s/d). Incidentally, it was found even in [10] also when the results were processed in terms of equivalent diameter, that ζ increases with increasing s/d (more slowly than for bundles with small relative pitch). In [11], for longitudinally washed bundles with large relative pitch, the correlating formula obtained for calculation of hydraulic resistance,

$$\xi = 0.3164\ \mathrm{Re}^{-0.25}\ (s_1 s_2/d^2)^{0.20}, \tag{1}$$

which is valid for Re = (5 − 60) · 10^3; $s_1 s_2/d^2 = 2.68 - 5.80$. The results of [10] for staggered bundles, and the data of [12] for corridor-type bundles were used in the generalization. The characteristic length used was the equivalent diameter. In (1) d is the outside diameter of the tubes, and s_1 and s_2 are the longitudinal and transverse pitches of the tubes in the bundle.

From the foregoing, we regard the arguments of the authors of the comments as unconvincing.

Naturally, the formula obtained in [1] will be refined as experimental data accumulate. Even at the present time, however, when sufficient experimental material has accumulated on hydraulic losses in channels of non-circular shape, and in particular, in longitudinally washed staggered tube bundles, wide use is fully warranted of the recommendations for calculation of hydraulic resistance for such channels according to the tube data, using the equivalent diameter as characteristic length. Such recommendations continue to appear, even recently, for example [13, 14]. Therefore, the authors of [1] considered it expedient in the example of longitudinal washing of staggered tube bundles to show that the use of these recommendations leads to coarse errors, and to bring forward the appropriate generalization of the relation for calculation. This permits us to ask in general if it is necessary to reject the above recommendations in all cases of calculation of non-circular channels for which there are direct experimental data. Whether or not the experimental data on non-circular channels is sufficient, these recommendations would be opportune as a first approximation for some types of channels. At present, when the need for accurate calculations is increasing, while the experimental data on many types of chennels is sufficient for obtaining relations for calculation, publication of the above-mentioned recommendations becomes harmful, since it leads to serious errors, to say nothing of the fact that these recommendations contradict the theory of similarity.

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Sergo Ordzhonikidze Aviation Institute, Moscow