PRESSURE DROP ANALYSIS IN THE CS INSERT COIL

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ABSTRACT

The Central Solenoid Model Coil (CSMC) and the CS Insert Coil (CSIC) were tested during the spring and summer of 2000 at JAERI Naka, Japan, within the framework of the ITER large projects. The CSIC is a single-layer one-in-hand solenoid inserted in the bore of the CSMC. It uses a Nb_3Sn dual-channel cable-in-conduit conductor (CICC), about 140 m long, cooled by forced flow supercritical HeI nominally at 4.5 K and 0.6 MPa. The friction of the helium flow in the conductor plays a fundamental role in assessing the total mass-flow rate and its repartition between the central cooling channel and the annular bundle region. In turn, these may significantly influence, e.g., quench and/or heat slug propagation in the coil. In the CSIC these issues are complicated further by the fact that different friction characteristics were observed in different phases (e.g., with or without current) of the experimental campaign. Here we present and discuss a selection of the CSIC experimental data of pressure drop vs. mass-flow rate, which were measured for the first time on a full-size ITER conductor in cryogenic conditions during the CSMC and CSIC tests, and compare with predictions based on existing correlations for the friction factor f_H in the central channel and f_B in the cable bundle, as a function of the respective Reynolds number Re_H and Re_B. Finally, we derive an ad-hoc correlation for f_B, to be used in case of operation of the CSIC with transport current, under the assumption that the central channel stays unchanged.

INTRODUCTION

The subject of helium friction in a CICC has received some attention over the years (see, e.g., [1]) because of its importance in determining the pressure drop along the

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conductor. More recently, attempts have started to develop general correlations based on room temperature data, e.g., for the central channel friction [2], to be eventually applied to cryogenic conditions in hydrodynamic similarity.

Coming to the CSIC, a preliminary overview of the experimental data on friction was given in [3], where also the behavior of different layers of the CSMC was considered in comparison. In particular, some correlation was observed between friction decrease compared to the virgin conductor state, and the strong Lorentz force (peak background field about 13 T and maximum transport current 40 kA), which acts on the conductor, although friction was considered globally and not separately for the central channel and the cable bundle. Also, some comparison was given between available correlations and experimental data. Here we wish to extend the work in [3] by appropriately taking into account the hydraulic features of the two conductor regions, by establishing the validity of some of the available correlations based on room-temperature data, and by proposing ad-hoc correlations to be used in the case of operation with current. We shall concentrate on the CSIC, while the pressure drop in the different layers of the CSMC is considered in a companion paper [4].

EXPERIMENTAL SETUP

The CSIC was well instrumented for detailed analysis. From the point of view of the present study the most relevant sensors are:

- Inlet (ICS-PT-IN) and outlet (ICS-PT-OUT) pressure sensors, from which the pressure drop $\Delta p_{raw} = p_{in} - p_{out}$ is computed;
- Inlet (ICS_FCT_INc) and outlet (ICS_FCT_OUTc) flow-meters;
- Inlet (ICS_TC_01) and outlet (ICS_TC_02) thermometers, from which the average thermodynamic state (density ρ (p_{av}, T_{av})) can be computed.

As to the effective pressure drop Δp, to be used in deriving friction factor correlations, it is necessary to correct Δp_{raw} by subtracting the gravity head $\Delta p_g = \rho(p,T)*g*h$ (with h ~ 5.3 m). As to the effective mass-flow rate (dm/dt), to be used in deriving friction factor correlations, we first of all compute the average $(dm/dt)_{av} = [(dm/dt)_{in} + (dm/dt)_{out}]$. Secondly, we tried and assessed the accuracy of this value by comparing it with the value $\rho*V_{HS}*A_{He}$, where V_{HS} is the average heat slug propagation speed which can be deduced from a set of heat slug propagation runs. The results of this analysis are shown in FIG 1 below and lead to the conclusion that the average mass-flow rate needs to be corrected as follows: $(dm/dt) = (dm/dt)_{av} - 0.84$ g/s.

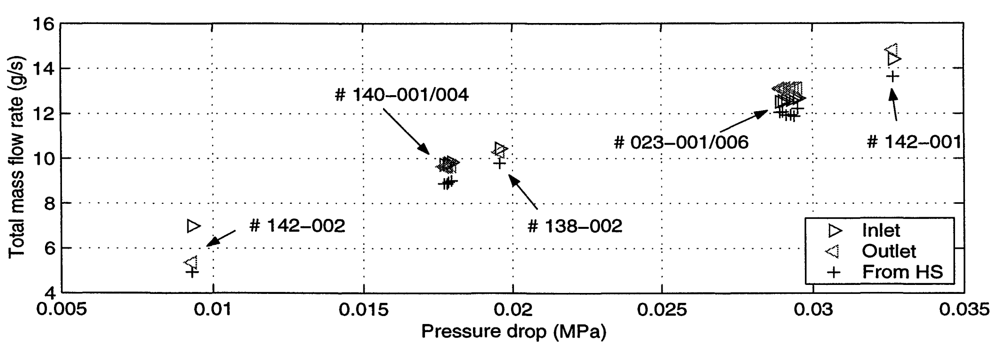

FIGURE 1. Assessment of flow-meter accuracy. Comparison between measured steady-state values of mass-flow rate at inlet and outlet (triangles), and independent estimate (+) derived from the experimental peak speed in several heat slug propagation shots. Notice that the difference between inlet and outlet values can be significant.

FRICTION CHANGES IN THE CSIC DURING THE EXPERIMENTAL CAMPAIGN

From the pressure drop measurement in the CSIC during different phases of the experimental campaign, it was possible to notice some changes occurring before, during and, to some extent, also after current operation. A selection of these data referring to steady-state conditions is collected in FIG 2 as a function of the total mass-flow rate in the conductor.

It may be noticed that there appears to be a reduction in friction during operation with current, compared to the conditions in the virgin state. This could arguably be attributed to a "third channel" with relatively low hydraulic impedance opening up inside the jacket between the jacket itself and the outer wrap. Also, some smaller difference is noticed between zero-current operation at the beginning and at the end of the campaign, possibly indicating that the Lorentz forces acting on the conductor could induce some form of permanent deformation. However, the latter conclusion should be taken with a grain of salt in view of the above-mentioned limitations in the accuracy of the flow measurement (see FIG 1).

A further indication of the change in friction due to current operation, this time in dynamic conditions, can be gained by analyzing current ramp-up shots at the beginning and at the end of the experimental campaign, as shown in FIG 3. It may be observed that in both cases the mass-flow rate in the CSIC is increasing during the ramp-up, although the pressure drop is decreasing, clearly indicating a dynamic change in friction factor. (Notice that the effect of AC losses in these runs is very modest, e.g., the temperature stays approximately constant at ~ 5.3 K, because the current in the CSMC was constant.)

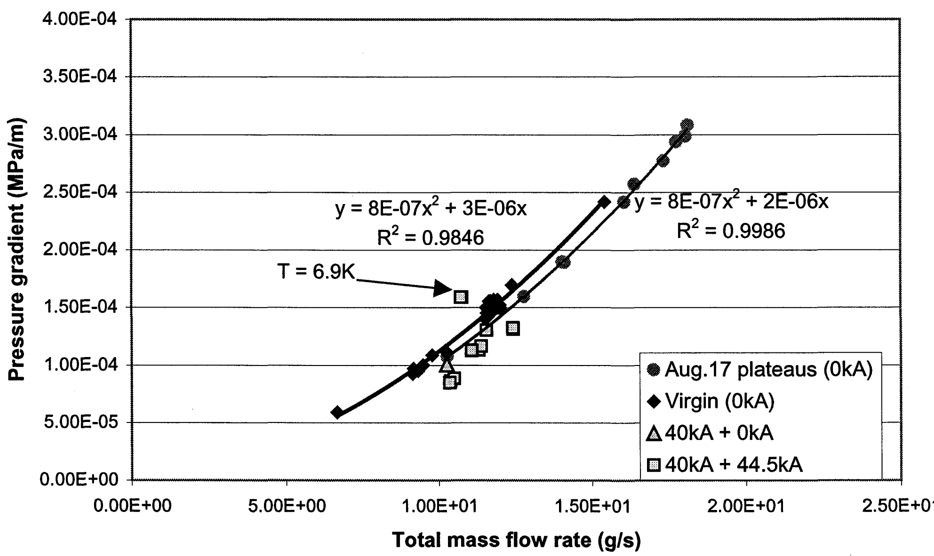

FIGURE 2. Change in CSIC hydraulic characteristic (effective pressure gradient $\Delta p/L$ vs. total effective mass-flow rate (dm/dt)) during the experimental campaign. Values at zero current are reported both for the virgin state (rhomboids, T = 4.4-4.6 K, p = 0.52-0.6 MPa) and at the end of the campaign (circles, T = 4.5-4.6 K, p = 0.55-0.62 MPa). Values with maximum current in the CSIC are reported both for maximum CSMC current (squares, T = 4.5-5.4 K, p = 0.55-0.63 MPa, except point @ T = 6.9 K) and for zero CSMC current (triangle). Trend-lines for the zero-current data before and after cycling have been added to guide the eye.

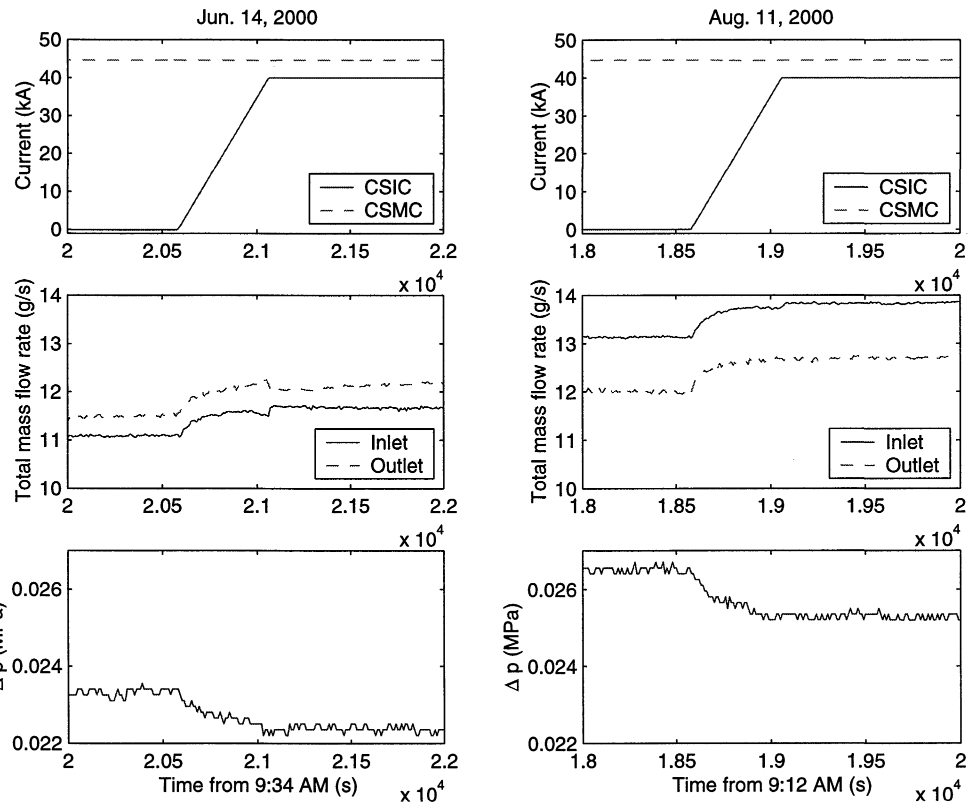

FIGURE 3. Effect of current on the CSIC hydraulic characteristic in dynamic conditions. Current ramp-up shots (# 174-001 and 343-003) to 40 kA, at the beginning (left column sub-plots) and at the end (right column sub-plots) of the experimental campaign. All raw data.

COMPARISON BETWEEN EXPERIMENTAL DATA AND PREDICTIONS BASED ON AVAILABLE CORRELATIONS FOR THE FRICTION FACTORS

As seen above, only the total mass-flow rate (as opposed to, separately, the mass-flow rate in the bundle $(dm/dt)_B$ and that in the central channel $(dm/dt)_H$) could be measured in the CSIC. Still, present-day thermal-hydraulic codes, e.g., M&M [5], describe different flows in the two regions of the CICC, and therefore separate friction factors, f_B and f_H respectively, are needed. It is therefore clear that one needs to rely on a correlation for least one of the two factors, and then use the CSIC data to assess the quality of the correlations for the other. However, there are other (room-temperature) data available [6], where both the total flow and the bundle flow only (blocked central channel) were measured in a similar conductor, allowing an independent assessment of both f_B and f_H.

Comparison with room temperature data

Here we want to first check the reliability of the Katheder correlation [7] for f_B, based on data measured on a CS1.2B conductor sample at room temperature [6]. The translation of the experimental data dm/dt vs. Δp into f_B vs. Re_B requires the definition of several geometrical parameters, whose values have been collected in TABLE 1.

TABLE 1 CS1.2B conductor sample data

	Parameter	Symbol	Value	Notes
	Length	L	6 m	
	Inner jacket diameter	D_{Jk}^{in}	0.039 m	
	Number of strands	N_{st}	1152	
	Strand diameter	d_{st}	0.81 mm	
Bundle	Average strand pitch	<cos(θ)>	0.93	From [9]
	Hydraulic diameter	D_{hB}	5.41×10^{-4} m	$D_{hB} = 4*A_{HeB}/P_B$ [a]
	Flow area	A_{HeB}	3.92×10^{-4} m^2	$A_{HeB} = \pi*[(D_{Jk}^{in})^2 - (D_{spiral}^{out})^2]/4 - N_{st}*(\pi*d_{st}^2/4) / \cos(\theta)$
	Void fraction	void	36.3 %	From [9]
Hole	Hydraulic diameter	D_{hH}	10 mm	$D_{hH} = D_{spiral}^{out} - 2*h$
	Flow area	A_{HeH}	7.85×10^{-5} m^2	$A_{HeH} = \pi*D_{hH}^2/4$
Spiral	Thickness	h	1.0 mm	
	Gap	g	3.0 mm	

[a] The major reason for the difference in D_{hB} with respect to, e.g., [6], is the evaluation of the bundle wetted perimeter P_B: We find $P_B = P_{st} + P_{wrap} = 2.90$ m, where $P_{st} = N_{st}*(\pi*d_{st})/\cos(\theta)$ * $\mathbf{(1+\cos(\theta))/2*(5/6)}$ = 2.54 m, and $P_{wrap} = (1 - \alpha_{Jk,St})$ * $[(\pi*D_{Jk}^{in} + \pi*D_{spiral}^{out}) + P_{wrap}^{subcable}] = 0.36$ m. We assumed a strand-sub-cable wrap contact fraction $\alpha_{Jk,St} = 0.25$, $P_{wrap}^{subcable} = 0.31$ m from [6], and flow only in the petals, in the central channel, and in the "triangles" between sub-cable and outer wrap, but negligible elsewhere (e.g., between outer wrap and jacket).

From this comparison it appears that, as reported in FIG 4a, if one takes into account the factor 5/6 in the definition of the wetted perimeter (as prescribed in [8]) the value of f_B from Katheder needs to be multiplied by a factor ~ 1.35 to obtain a good match with the experimental data of [6]. (Notice that, by chance, a good match *without* correcting factors could also be obtained if the factor 5/6 is not used, but this appears in contrast with the recipe

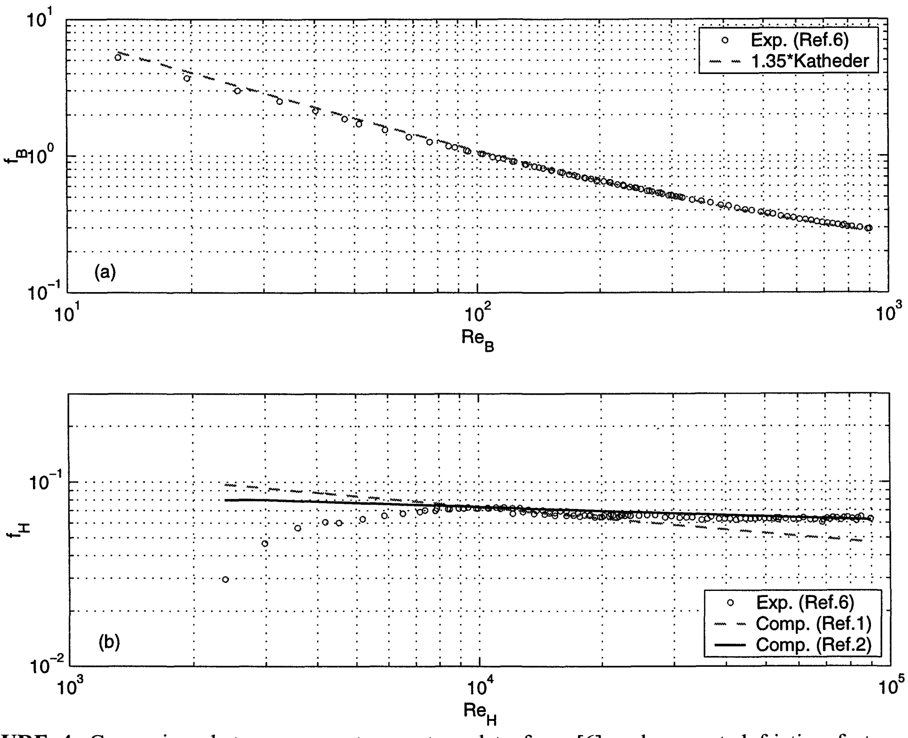

FIGURE 4. Comparison between room temperature data from [6] and computed friction factors, as a function of the respective Reynolds number. Bundle (a): the Katheder correlation [7] with 5/6 factor in the computation of the bundle hydraulic diameter [8] was used. Hole (b): comparison of ITER-QUELL correlation [1] (dashed) and correlation from [2] (solid).

TABLE 2. CSIC conductor data

	Parameter	Symbol	Value	Notes
	Length	L	142.34 m	Including joints
	Inner jacket diameter	D_{Jk}^{in}	0.039 m	
	Number of strands	N_{st}	1152	
	Strand diameter	d_{st}	0.81 mm	
Bundle	Average strand pitch	$<\cos(\theta)>$	0.93	Design value [a]
	Hydraulic diameter	D_{hB}	5.41×10^{-4} m	See TABLE 1
	Flow area	A_{HeB}	3.92×10^{-4} m^2	See TABLE 1
	Void fraction	void	36.3 %	
Hole	Hydraulic diameter	D_{hH}	9.8 mm	See TABLE 1
	Flow area	A_{HeH}	7.54×10^{-5} m^2	See TABLE 1
Spiral	Thickness	h	1.0 mm	
	Gap	g	2.8 mm	

[a] A value of 0.967 was more recently estimated, but no direct measurements are available yet.

presented in [8]).

Before performing the CSIC analysis strictly speaking, the data from [6] can also be used to assess, as done in FIG 4b, the relative accuracy of the available correlations for f_H, namely the ad-hoc ITER-QUELL correlation $f_H^{(1)}$ from [1], and the correlation $f_H^{(2)}$ derived in [2], based on and validated against room temperature data [1]. From the data in [6] (experimental pressure drop per unit length vs. mass flow rate, with open and close central channel), it is possible to compute the value of f_H as a function of Re_H *without using any correlation* (open symbols in FIG 4b). From FIG 4b, there is an evident difference at high Re_H between the trend deduced from the experimental data and the trend of the ITER-QUELL correlation [1]. The correlation from [2] seems instead to provide a better approximation of the experimental data in the relevant range $Re_H > 5\times10^4$.

Comparison with CSIC data at zero current

It is now interesting to compare global data obtained on the CS1.2 conductor and on the CSIC at zero current. This is done in FIG 5 below [2], using the CSIC conductor data given in TABLE 2. It appears that the global hydraulic impedance of the CSIC at zero current is (for unknown reasons - deformation/displacement inside the cable? tolerances during fabrication? cable twist pitches?) somewhat smaller than that of the CS1 conductor tested in [6], as the CSIC points lie below the extrapolation to higher Re of the data from [6]. This means that ad-hoc correlations for the CSIC need to be developed.

DEVELOPMENT OF AD-HOC CORRELATIONS FOR CSIC OPERATION

In view of the fact that no data with blocked central channel are available for the CSIC, which would allow an independent assessment of the quality of bundle and hole correlations,

[1] There are *caveat* in this comparison. First, the data in [6] are restricted to the range $2\text{-}3\times10^3 < Re_H < 10^5$, which is not completely relevant to the CSIC nominal conditions of operation. Second, QUELL data cover only the range $10^5 < Re_H < 10^6$, although the correlation in [1] was already checked against data obtained on the CS conductor at room temperature going down to $Re_H > 10^4$, see [1] and references therein. Third, the correlation in [2], was derived from data which cover only the range $5\times10^4 < Re_H < 10^6$.

[2] CSIC data in FIG 5 come from two different sets: 1) virgin state; 2) I = 0 part of Aug.17, 2000 tests. Data points were selected as follows: for set 1, night data were arithmetically averaged, resulting in 28 data points (one for each night); for set 2, plateau values were selected for steady state condition, resulting in another 10 data points.

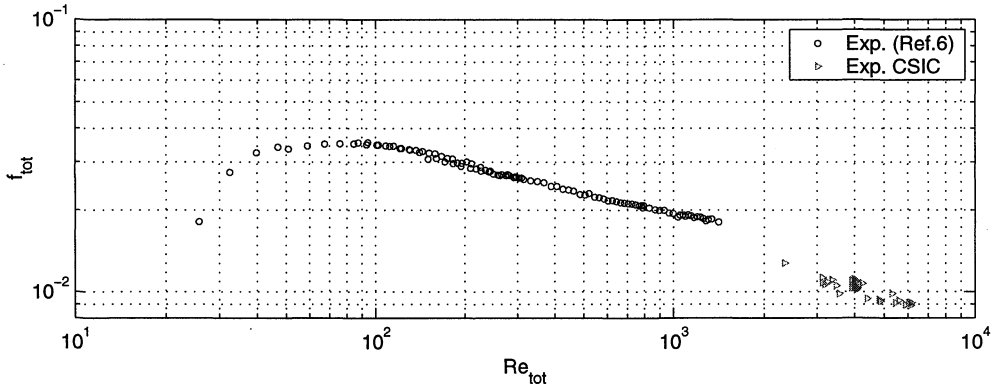

FIGURE 5. Total (bundle + hole) friction factor f_{tot} vs. total Reynolds number Re_{tot} in CS1.2 (circles) and CSIC at zero transport current (triangles). f_{tot} and Re_{tot} are computed from the standard definitions (see, e.g., [2]) using the total mass-flow rate, the total helium flow area and the total wetted perimeter.

we have to decide whether to use established correlations for f_B *or* for f_H (and to develop the other from the CSIC data). Based on our experience with compacting the CS2 cable, the spiral in the CS2 conductor does not deform up to ~10% void fraction. Therefore, we make the assumption that negligible changes with respect to the design took place in the central channel, and, considering the results of the previous sections, we stick to the recipe in [2] for f_H, which was shown above to be the most successful in the reproduction of room-temperature data.

If, under these assumptions, we use the CSIC data for obtaining an ad-hoc f_B, the results for the different phases of the experimental campaign are summarized in FIG 6.

Taking as reference for this discussion the values of f_B deduced for the virgin state, it appears that some of the observations already drawn from FIG 1 can be repeated and extended, namely:

1. Some limited permanent change seems to have occurred in the conductor, as shown from the reduction of f_B in the zero-current Aug.17 data;
2. Lorentz-force effects due to self-field only (single point) are limited, but they become much more significant as also the CSMC is charged to reach 13T.

For each of the above situations, power fits of $f_B(Re_B)$ have been derived using EXCEL and are also shown in FIG 6. Notice that at peak current, $f_B = 0.0162 \pm 5\%$ is about a constant.

From the point of view of flow repartition, it is finally worthwhile to mention that, under the assumptions which led to FIG 6, in the CSIC the fraction of mass-flow rate in the central channel should go from ~ 55 % without current to ~ 45-50 % at maximum current. Notice that this is rather different from the repartition in QUELL – central channel fraction ~ 70-80 % [1] – and from the repartition which can be deduced from the data in [6] – central channel fraction decreasing down to ~ 65 % at the highest mass-flow rate tested.

CONCLUSIONS

The apparently simple but in practice subtle problem of helium friction in the CSIC has been considered. In different phases of the experiment (with and without current, before and after cycling) the conductor showed somewhat different behavior from this point of view. Established correlations have been evaluated against room-temperature data and applied to the CSIC. For the cases with maximum current in both the CSIC and the CSMC

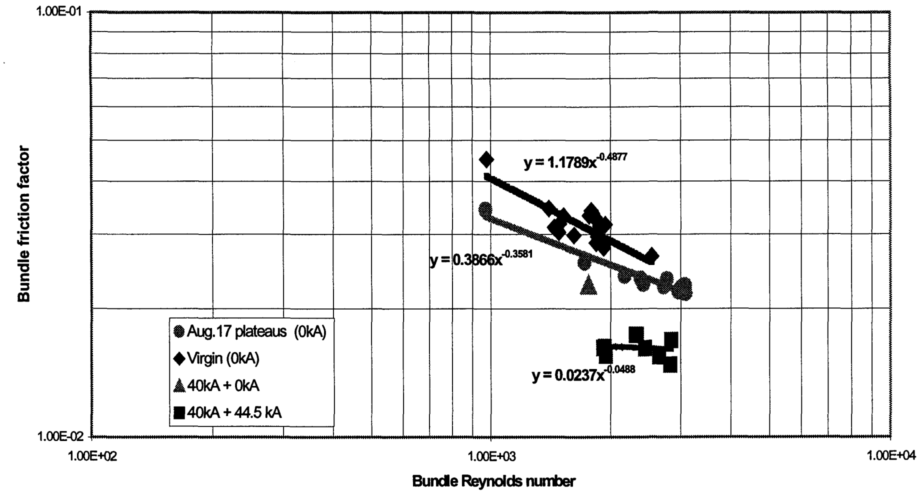

FIGURE 6. Bundle friction factor deduced from CSIC data for different experimental conditions, assuming f_H from [2].

(relevant to, e.g., many of the stability/quench runs) the combination of f_H from [2] together with $f_B \sim 0.0162$ provides a reasonable approximation of the CSIC data. In the CSIC only about 50 % of the total mass-flow rate should flow in the central channel.

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