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Efficacy of Using the Loss Factor to Estimate the Power Requirements of Wind and Water Tunnels with Varying Cross Sections

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***Abstract**: Estimations of power requirements in wind tunnels are based on the assumption that pressure losses are proportional to the square of the flow velocity. This assumption is invalid for certain flow conditioners, particularly honeycombs and wire screens. Therefore, current methods of estimating power requirements across a range of flow velocities are, theoretically, prone to errors. This paper will review the existing approaches and show that the resulting inaccuracies are small. Furthermore, best-practice suggestions are given to further minimise the impacts of these errors on wind tunnel design.*

***Keywords**: Power requirements, loss factor, wind tunnel, water tunnel*

1. Introduction

In the design stage of building a wind or water tunnel, it is essential to predict the power requirements and pressure losses of the facility. Without an accurate estimation of these characteristics, designers run the risk of including the wrong size or even type of flow fan.

The source of energy losses in wind tunnels are diverse but generally come in two categories: losses caused by the facility's geometry and losses due to the flow conditioners placed within the machine. The former includes components such as nozzles (contracting sections), diffusers (expanding sections), turns and straight sections. Flow conditioners are devices used to modify flow characteristics to improve the experimental environment. For instance, wire screens are used to increase flow uniformity, honeycombs are used to decrease turbulence, and turning vanes decrease energy losses within turns.

Extensive literature exists on the pressure losses of all of these flow conditioners. Barlow's "Low-Speed Wind Tunnel Testing" in particular, is an invaluable source of information [1]. While existing publications consider the impact of varying cross-sectional areas, they assume that losses are proportional to the square of the flow velocity. However, this relationship is only valid for certain types of flow conditioners. The work herein will assess the impact on real-world power requirements when this assumption is invalid.

2. Adapting the Pressure Loss Factor

As flow passes through various components in a wind tunnel, static pressure (potential energy) is converted to heat through drag and turbulence. This change in pressure is said to be energy that is *lost* to the system. The amount of energy lost by a specific component can be described by the loss factor. The relationship between the drop in pressure (Δp), loss factor (K), fluid density (ρ), and velocity (U) is shown in equation (1).

$$\Delta p = \frac{1}{2} K \rho U^2 \tag{1}$$

If there is a change in velocity or area, as is the case in diffusers and nozzles, the upstream conditions should be used as a basis for calculations. Multiplying both sides of the equation above by the volumetric flow rate (Q) yields equation (2).

$$Q\Delta p = \frac{1}{2} Q K \rho U^2 \tag{2}$$

Equation (5) is derived by substituting the relationships for power (P) and volumetric flow rate (Q) into equation (2), where A is the cross-sectional area.

$$P = Q\Delta p \tag{3}$$

$$Q = AU \tag{4}$$

$$P = \tfrac{1}{2}\rho KAU \tag{5}$$

If there are multiple components in a flow circuit, with various areas, velocities, and loss values, the total power requirement can be estimated using equation (6), assuming incompressible flow. Different subscripts represent distinct wind tunnel locations.

$$P = \sum_{i=1}^{n} \frac{1}{2}\rho K_i A_i U_i^3 \tag{6}$$

As wind and water tunnels can have a large variety of different cross-sectional areas, it is advantageous to introduce the concept of a generalised local area ratio ($\mathcal{R}$). This is simply the ratio between a local area (A_i) and the area of the test section (A_1) as shown in equation (7).

$$\frac{A_i}{A_1} = \mathcal{R} \tag{7}$$

The generalised area ratio can then be used to express local areas (A_i) and velocities (U_i) in terms of test section velocity (U_1) and area (A_1).

$$A_i = A_1\mathcal{R}_\mathrm{i} \tag{8}$$

$$U_i = \frac{U_1}{\mathcal{R}_\mathrm{i}} \tag{9}$$

Substituting these ratios into equation (6), all terms can be expressed as a factor of area ratio, as shown in equation (10) and the simplified equation (11).

$$P = \sum_{i=1}^{n} \frac{1}{2}\rho K_i A_1 \mathcal{R}_i \left(\frac{U_1}{\mathcal{R}_i}\right)^3 \tag{10}$$

$$P = \sum_{i=1}^{n} \frac{1}{2}\rho A_1 U_1^3 \left(\frac{K_i}{\mathcal{R}_i^2}\right) \tag{11}$$

Rearranging these relationships in terms of main velocity results in equation (12), which indicates the flow velocity in the test section for a specific power input.

$$U_1 = \sqrt[3]{P \div \frac{1}{2}\rho A_1 \div \sum_{i=1}^{n} \frac{K_i}{\mathcal{R}_i^2}} \tag{12}$$

Keeping these relationships in mind, the following sections will detail more accurate ways of predicting pressure losses for wire screens and honeycombs.

3. The Loss Factor in Wire Screens

The pressure loss through a wire screen is largely dependent on the screen's porosity. The wire screen porosity (ϕ) can be calculated using equation (13), where d_{wt} is the wire thickness and d_{wp} is the wire pitch.

$$\phi = \left(1 - {d_{wt}}/{d_{wp}}\right)^2 \tag{13}$$

The way the wires are woven also has a slight impact on performance, but this work will focus on the standard plain weave type screens. Based on the screen's porosity and weave-type, the method outlined by Wu et al. can be used to estimate the pressure loss [2]. This approach ignores the sinusoidal structure of the wires caused by weaving the screen and therefore slightly underestimates porosity. In addition to porosity, the surface area to volume ratio (S_v) has to be found using equation (14), where d_{wn} is the number of wires per linear metre.

$$S_v = \sqrt{\frac{1}{d_{wn}^2} + d_{wt}^2} \times d_{wn}^2 \tag{14}$$

Furthermore, the equivalent spherical diameter (D_P) has to be calculated using equation (15). It is essentially an estimation of the size of the sphere required to influence the flow to the same extent as the particular wire screen.

$$D_P = 6/S_v \tag{15}$$

Once these parameters have been determined, the specific Reynolds Number (Re_w) of the wire screen may be calculated using equation (16). As per usual, U, ρ and μ represent fluid velocity, density and dynamic viscosity respectively.

$$Re_w = \frac{(1-\phi)D_P U \rho}{\mu} \tag{16}$$

After Re_w has been obtained, and the mesh thickness d_m has been measured, the pressure drop ΔP can be found by estimating the viscous ($\mathrm{K_{SD}}$) and inertial (K_{SF}) porous resistance.

$$\Delta P = K_{SD} + K_{SF} \tag{17}$$

$$K_{SD} = \left[250\,\frac{1-\phi}{Re_w}\right] \times \left[\frac{d_m U^2 \rho (1-\phi)}{\phi^3 D_P}\right] \tag{18}$$

$$K_{SF} = \left[1.69\left(\frac{1-\phi}{Re_w}\right)^{0.71}\right] \times \left[\frac{d_m U^2 \rho (1-\phi)}{\phi^3 D_P}\right] \tag{19}$$

From a dimensional analysis of equations (18) and (19) it is clear that the pressure loss in wire screens is not proportional to the square of the velocity. The viscous resistance is proportional to u, while the inertial resistance is proportional to $u^{1.29}$. As will be shown later, assuming a constant standard loss factor can lead to a slight underestimation of pressure loss.

4. The Loss Factor in Honeycombs

Honeycombs for flow conditioning come in various shapes and sizes as shown in Fig. 1. For these honeycombs, given a ratio of tube length (L) to hydraulic diameter (D_H) of $L/D_H = 6.0$, the loss factors are 0.30, 0.22, and 0.20 respectively [1]. As these loss factors are limited to specific honeycomb lengths, a more thorough exploration of the loss factor will follow.

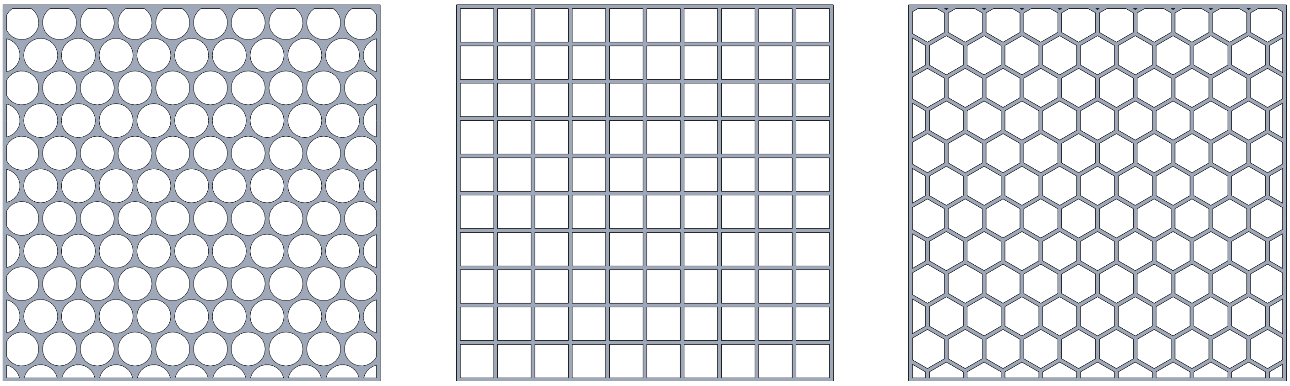

Fig. 1. Tubular honeycomb (left), rectangular honeycomb (centre), and hexagonal honeycomb (right).

The analysis herein will be based on the common tubular honeycomb, which is comprised of thin-walled tubes arranged in a hexagonal pattern. The main geometric characteristics of this honeycomb type are shown in Fig. 2.

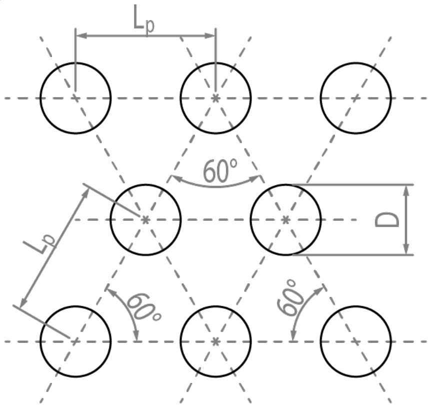

Fig. 2. Geometry of a honeycomb consisting of thin-walled tubes in a hexagonal arrangement, with internal diameter (D) and pitch (L_p).

Using tube pitch (L_p) and tube internal diameter (D) the porosity of the honeycomb (ϕ) can be calculated using equation (20) [3].

$$\phi = 0.9069 \times D^2 \div L_p^2 \tag{20}$$

Various methods can be used to predict the pressure drop across honeycombs. The work herein will focus on the publications of Innocentini et al. [4], as well as Eckert et al. [5].

4.1 Adapting Innocentini's approximations to Tubular Honeycomb

Innocentini approximation is an adaption of Ergun's equation, which itself is used to predict the pressure drop across densely packed granular media, such as crushed glass filters. In contrast, Innocentini investigates web-like filament structures and therefore aimed to replace mean particle diameter (d_p) with the specific surface (S_V), i.e., the total particle surface per unit volume of the particle. However, tubular honeycomb is more structured and its hydraulic cylinder (d_c), the cylindrical form of the hydraulic diameter, can easily be calculated as shown in equation (21).

$$d_c = 4\frac{V_{flow}}{S_w} \tag{21}$$

Here, V_{flow} is the volume available for the flow (i.e., within the confines of the honeycomb, but not occupied by honeycomb material), and S_w is the total wetted surface. In equation (22), this result is equated with the alternative equation for hydraulic diameter, resulting in equation (23).

$$d_c = 4\frac{1-\phi}{\phi S_V} \tag{22}$$

$$\frac{V_{flow}}{S_w} = \frac{1-\phi}{\phi S_V} \tag{23}$$

The total wetted area is the surface area of a single tube, while the volume available for flow is the imaginary *hexagonal* volume the tube occupies within the honeycomb. The specific surface can be isolated as shown in equation (24).

$$S_V = \frac{1-\phi}{\phi} \times \frac{S_w}{V_{flow}} \tag{24}$$

This results in a new expression for particle diameter, shown in equation (25).

$$d_p = \frac{6}{S_V} = 6 \times \frac{\phi}{1-\phi} \times \frac{V_{flow}}{S_w} \tag{25}$$

With this new expression for particle diameter, the viscous (K_{HD}) and inertial (K_{HF}) terms for pressure loss can be evaluated as shown in equations (26) and (27). Some literature states these terms in the way they are shown here, however, other sources show them as the fractional inverse.

$$K_{HD} = \frac{150(1-\phi)^2}{\phi^3 d_p^2} \tag{26}$$

$$K_{HF} = \frac{1.75(1-\phi)}{\phi^3 d_p} \tag{27}$$

These terms can then be used to evaluate the pressure drop, based on the length of the honeycomb (L), using equation (28), where ϕ is porosity, d_p is the particle diameter, ρ is the fluid density, μ is the dynamic viscosity and U is the fluid velocity.

$$\Delta P = L(K_{HD}\mu U + K_{HF}\rho U^2) \tag{28}$$

Once again, it is clear that the loss factor is not proportional to the square of the velocity, but to a combination of U and U^2 [4].

4.2 Adapting Tubular honeycomb losses based on Eckert's approximations

Eckert's approach is fundamentally different to the previous method and is based on empirical data of thin-walled flow straighteners (i.e., actual honeycomb structures). First, a Reynolds Number (Re_ε) has to be calculated based on flow velocity (U), honeycomb surface roughness (ε) and kinematic viscosity (ν), as shown in equation (29).

$$Re_\varepsilon = \frac{U\varepsilon}{\nu} \tag{29}$$

A friction factor (f_e) can then be found based on the hydraulic diameter (D_H) of a single honeycomb tube using either equation (30) or equation (31).

$$f_e = 0.375\, Re_\varepsilon^{-0.1} \left(\frac{\varepsilon}{D_H}\right)^{0.4} \quad when \quad Re_\varepsilon \leq 275 \tag{30}$$

$$f_e = 0.214 \left(\frac{\varepsilon}{D_H}\right)^{0.4} \quad when \quad Re_\varepsilon > 275 \tag{31}$$

Once the friction factor has been computed, the loss factor (K) can be determined using (32), where L and ϕ represent honeycomb length and porosity respectively.

$$K = f_e \left(3 + \frac{L}{D_H}\right)\left(\frac{1}{\phi}\right)^2 + \left(\frac{1}{\phi} - 1\right)^2 \tag{32}$$

The loss factor generated by this approach, once again, is not proportional to U^2. Below a surface roughness Reynolds number of 275, the loss factor is proportional to $U^{-0.1}$. Above said this threshold, the loss factor is assumed to be constant [5].
The main drawback of this method is its dependency on surface roughness. It is the base of the Reynolds number and is also used in every single term of the final equation. Hence, a small error in surface roughness has a large impact on the final pressure drop prediction.

4.3 Loss Factors in Computational Fluid Dynamic Codes

Interestingly, common computational fluid dynamics (CFD) codes such as OpenFOAM and Ansys Fluent do not use the experimentally proven methods estimations outlined above. Instead, they use the traditional Darcy-Forchheimer equation [6]. This formulation also involves a viscous (K_D) and inertial (K_F) term, commonly known as the Darcy and Forchheimer terms respectively [7], and are shown in equation (33).

$$\Delta\mathrm{P} = \mathrm{K}_D \mu U + K_F \frac{1}{2}\rho U^2 \tag{33}$$

This relationship is used to estimate the pressure drop of both honeycombs and wire screens. The main difference between wire screens and honeycombs is merely the implementation. To simulate a wire screen, CFD simulations usually use a virtual internal boundary and multiply the pressure drop obtained from the Darcy-Forchheimer equation by some virtual length L. Honeycombs on the other hand, are simulated by declaring that certain zones within the simulation are honeycomb zones and an additional multiplication with the length of the honeycomb is not needed.

5. Evaluation and Discussion

The previous sections outlined more precise methods of estimating pressure losses in honeycombs and wire screens. These predictions can be used to evaluate the efficacy of estimating pressure losses based on the assumption that the loss factor is proportional to the square of the velocity. Power requirements have been calculated based on a wind tunnel cross-section of $1m^2$.

5.1 Honeycombs

Some of this section is based on the honeycomb geometry used in the Deep Ocean Basin in Singapore (DOBS). The honeycomb used in this facility consists of polycarbonate tubes, with an inner diameter of 6.8mm, and a wall thickness of 0.1mm, resulting in a pitch of 7.0mm. Some experimental pressure analysis has been conducted by Agency for Science, Technology and Research (A*STAR). The length of the tubes has been assumed to be 42mm, and is therefore in line with the literary values, which are given for $L/D_H = 6.0$. Four methods of estimating the loss factor and pressure drop are compared:

- The standard method of assuming that the pressure loss factor is constant and proportional to the square of the velocity. A loss factor of 0.22 has been used as suggested by Barlow et al. [1].
- Using the Darcy-Forchheimer equation, based on the experimental findings of A*STAR. They estimated $K_D = 7 \times 10^5$ and $K_F = 5$.
- Using Eckert's approximation and assuming a surface roughness of 0.0025mm, which is standard for plastic Perspex and drawn tubing.
- Using Innocentini's approximation, which does not require the specification of any additional constants.

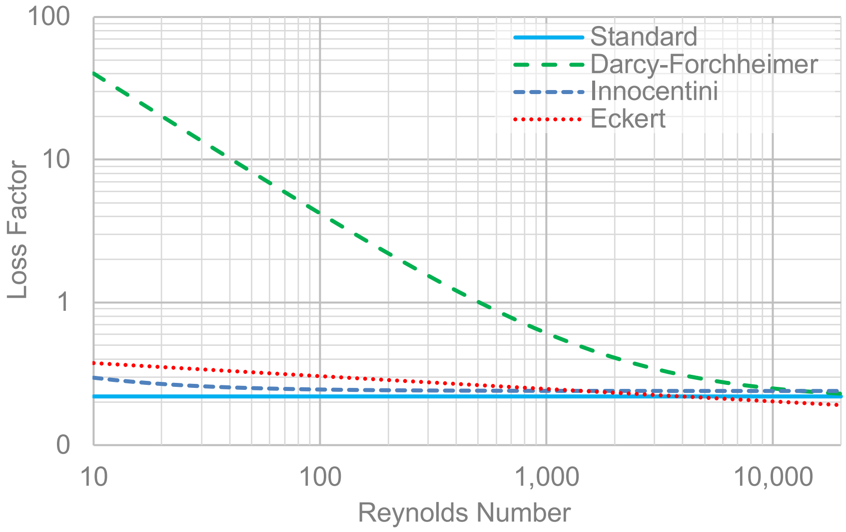

Fig. 3. Loss factor with increasing Reynolds number based on honeycomb tube diameter.

The change in loss factor at various flow speeds is shown in Fig. 3. It is evident, that the loss factor predicted by the Darcy-Forchheimer equation varies substantially from the other prediction. However, the predictions do converge at a Reynolds number of approximately 20,000. At this point, the standard approach, the Darcy-Forchheimer equation and Innocentini's approximation predict loss factors of 0.220, 0.230 and 0.240 respectively. The loss factor predicted by Eckert's approximation is notably lower at 0.191.
The impact of the lower loss factor generated using Eckert's approximation is clearly seen in Fig. 4. The estimated power requirements are approximately 20% lower than the other three predictions.
To bring Eckert's approximation in line with the other predictions, the surface roughness would have to be increased from 2.5μm to 5.1μm. This micrometre-scale adjustment highlights the strong dependency on the surface roughness of this approach.

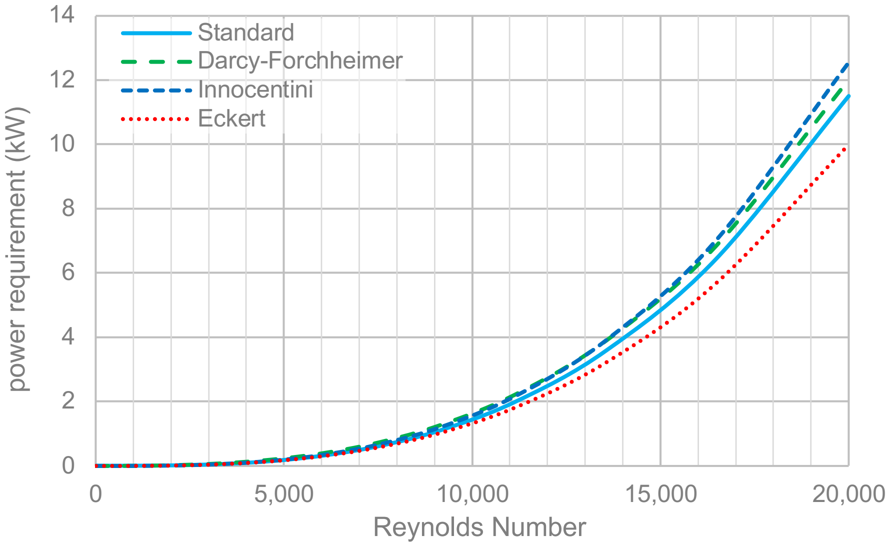

Fig. 4. Power requirement with increasing Reynolds number based on honeycomb tube diameter.

Both the Darcy-Forchheimer equation and standard constant loss factor prediction were based on some experimental data. Considering that the estimates generated with Innocentini's method are purely theoretical, it is remarkable how close they are to the experimental results. The proximity of these results also reaffirms the validity of using the standard loss factor to estimate pressure losses and power requirements of honeycombs in wind and water tunnels.

5.2 Wire Screens

The pressure drop approximation for wire screens presented by Wu et al. is an empirical equation based on a meta-analysis of various publications. As shown in Fig. 5, this loss factor does not scale with the square of the velocity. When estimating wind or water tunnel performance, it is usually most important to find the power requirements at the top flow speed of the facility, where they will be highest. Therefore, estimating the loss factor at the maximum flow velocity using Wu's approximation and assuming this value is constant throughout the various velocities, is a decent compromise. This approach is labelled as "Standard" Fig. 5.

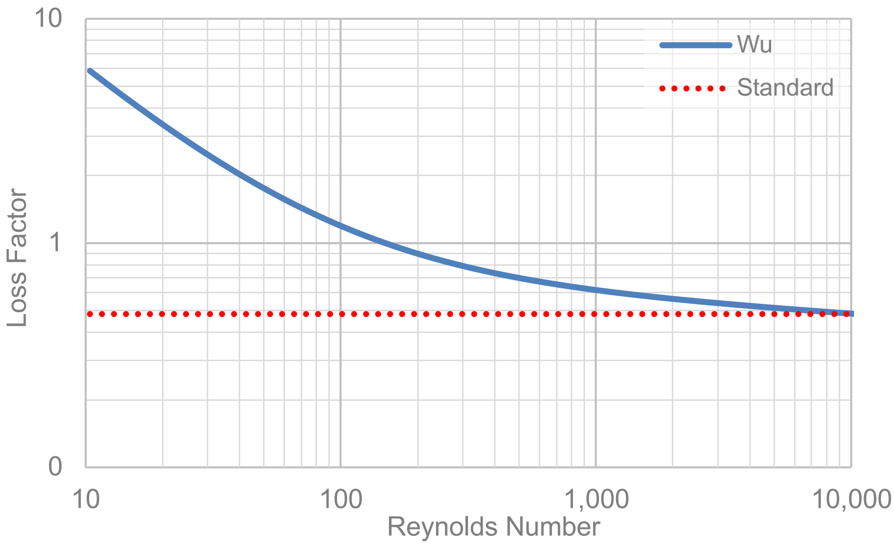

Fig. 5. Loss factor with increasing wire screen Reynolds Number (Re_w)

For the estimation of power requirements, the size of the wire screen was set at 1m^2. The wire thickness was assumed to be 1mm, the wire pitch is 5mm and the resulting gap is 3mm. This results in a pressure loss coefficient of 0.48 at a wire-based Reynolds number of 10,000. As is evident from Fig. 5, this is an underestimation of the loss factor below this flow speed. Nevertheless, Fig. 6 shows that this is barely noticeable in the resulting estimation of power requirements. Therefore, it is clear that the standard approach of using the loss factor can also be used to estimate the power requirements of screens.

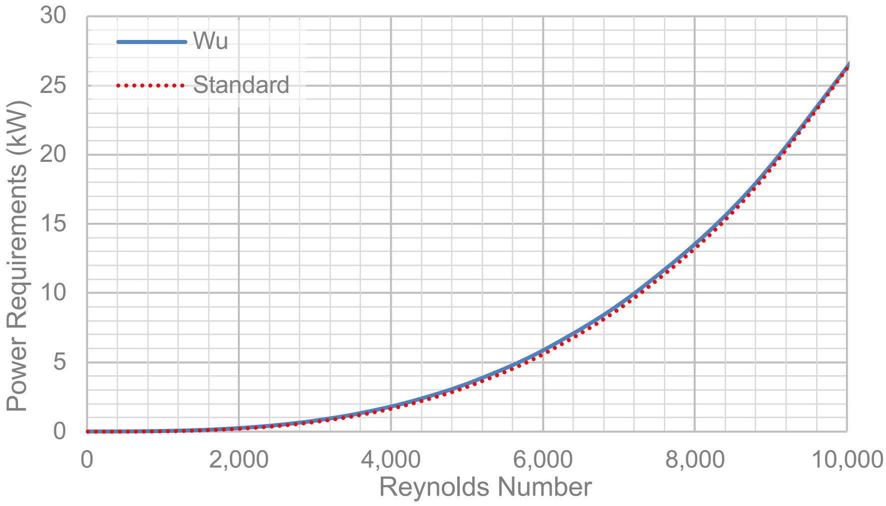

Fig. 6. Power requirement with increasing wire screen Reynolds Number (Re_w)

6. Conclusions

It has been shown that pressure losses and power requirements can accurately be estimated based on a standard loss factor approach. Some errors are caused by the fact that the real loss factor does not scale perfectly with the square of the velocity. To minimise these errors, the loss factor should therefore be estimated at the maximum desired flow velocity of the particular wind tunnel section. Thus, two geometrically identical wire screens would have different loss factors if they were situated in sections with different flow velocities.

The pressure loss estimations by Wu et al. are highly accurate as they are empirical equations based on a meta-analysis of multiple publications and flow velocities. Unfortunately, the same does not exist for honeycombs. If no experimental data exists, and the L/D_H ratio is not equivalent to the standard 6.0, then Innocentini's approximation is a fairly accurate alternative. Eckert's approximation might be improved with a better estimation of the exact surface roughness of the honeycomb material, although further research is required to confirm.

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