General model for prediction of pressure drop and capacity of countercurrent gas/liquid packed columns

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A generalized model has been developed for the prediction of pressure drop and flooding in packed columns in which gas and liquid flow countercurrently. The model has been validated for a wide variety of packings, both random and structured. A single mathematical expression is used to describe all flow regimes: dry gas, irrigated gas flow below the load point, loading region, and flooding. The approach to the model development is fundamental in character and is an improvement over models published earlier.

Keywords: countercurrent; packed columns; pressure drop; mathematical model

Nomenclature

\[ a \] Specific surface area of packing (m\(^2\) m\(^{-3}\))
\[ c \] Exponent in Equation (10)
\[ C_1, C_2, C_3 \] Constants in Equation (7)
\[ d_n \] Nominal diameter of packing element (mm)
\[ d_p \] Particle diameter, \( d_p = 6(1 - \varepsilon)/a \) (m)
\[ d'_p \] Particle diameter including surface liquid (m)
\[ D_c \] Column diameter (m)
\[ f \] Friction factor for flow through a packed bed
\[ f_e \] Friction factor for Ergun equation
\[ f_o \] Friction factor for flow past a single particle
\[ f_s \] Friction factor for flow past a particle in a bed
\[ Fr_L \] Froude number for liquid [Equation (14)]
\[ g \] Gravitational constant (m s\(^{-2}\))
\[ h \] Liquid hold-up in a packed bed (m\(^3\) m\(^{-3}\))
\[ h_0 \] Liquid hold-up below the loading point (m\(^3\) m\(^{-3}\))
\[ n \] Exponent in Equation (1)
\[ p \] Pressure (N m\(^{-2}\) or bar)
\[ Re_e \] Reynolds number for the gas = \( d_p U_g \rho_g / \mu_g \)

\[ S \] Cross-sectional area of column (m\(^2\))
\[ U_g \] Superficial gas velocity through a packed bed (m s\(^{-1}\))
\[ U_L \] Superficial liquid velocity through a packed bed (m s\(^{-1}\))
\[ U_o \] Velocity for suspending a single particle (m s\(^{-1}\))
\[ U_S \] Velocity for fluidizing a bed of particles (m s\(^{-1}\))
\[ Z \] Total height of packing (m)

Greek letters

\[ \Delta p \] Pressure drop (N m\(^{-2}\))
\[ \Delta p_d \] Pressure drop through an unirrigated (dry) bed (N m\(^{-2}\))
\[ \Delta p_{in} \] Pressure drop through an irrigated bed (N m\(^{-2}\))
\[ \varepsilon \] Bed void fraction (porosity) (m\(^3\) m\(^{-3}\))
\[ \mu \] Absolute viscosity (kg (ms)\(^{-1}\))
\[ \sigma \] Surface tension (N m\(^{-1}\))
\[ \rho \] Density (kg m\(^{-3}\))

Subscripts

\( f \) Flooding
\( g \) Gas
\( L \) Liquid

Numerous attempts have been made to describe the hydrodynamic behaviour of packed columns operating as countercurrent gas/liquid contactors. These attempts have ranged from the very empirical to the semi-empirical and have achieved moderate success for some applications within certain limited ranges of operating conditions. In
the present work, a generalized approach is developed for gas/liquid packed columns, one that covers all of the regions normally encountered in operation, from dry gas flow around a single packing particle to gas-liquid counterflow under loadings up to the flood point. The approach is fundamental in character and based on the description of the system pressure drop and liquid hold-up under varying conditions. A single mathematical expression is used to describe all regimes, and its derivative can be used to predict the flood point.

Two constraints that were placed on the development of this new approach were that the number of correlating constants should be minimized and that the fundamental geometric properties of the packings, such as surface area and void fraction, should suffice in most cases to account for differences in packing behaviour. Within these constraints the result should be a more generally applicable and rigorous approach to predicting hydrodynamic behaviour.

The two basic approaches to describing the hydrodynamics of a packed column are the channel model and the particle model. In the first, the gas is assumed to be flowing upward inside numerous small channels having some characteristic dimension; as liquid flows down the 'walls' of the same channels it reduces the available cross-sectional area for gas flow, thus causing increased pressure drop. In the particle model the gas is assumed to flow around a packing particle having a characteristic dimension and the liquid acts to increase this dimension by its adherence to the particle surface. The presence of the liquid also reduces the void fraction of the bed.

Several authors\(^1\) have used the channel model to describe pressure drop in beds of random and structured packings for gas/liquid service, with some success. Single phase flow through packed beds, using the particle model, has been described by Ergun\(^4\), Braue\(^8\) and Rose\(^6\), and others. The particle model was used in this work; it has not previously been formally applied to gas/liquid contacting.

**Dry pressure drop in a packed bed**

The flow of a single phase through a packed bed has been studied extensively for many chemical engineering applications, particularly for the design of fixed catalytic beds. Extensive work has also been done in the area of fluidized beds where the porosity of the bed is a variable that depends on the geometry as well as the loading. Conventional packed columns for gas/liquid contacting are not fluidized beds, but they are similar in that their effective bed porosity also changes with geometry and loading because of liquid hold-up. Richardson and Zaki\(^7\) developed the following relationship between gas velocity and porosity for fluidized beds

\[
\frac{U_s}{U_0} = E^n (1)
\]

where \(U_s\) is the superficial velocity required to suspend a multitude of particles; \(U_0\) is the superficial velocity required to suspend a single particle; \(E\) is the void fraction of the fluidized bed; and the exponent \(n\) is a function of the particle Reynolds number as shown in Figure 1. In the

Friction factors and pressure drop

In Equations (1) and (2), the assumption is made that the fluid behavior is not affected by the swarm particles. The pressure drop in a fluidized bed in equilibrium is equal to the weight of the bed

\[
\Delta p_s = ZS(1 - \varepsilon)\Delta \rho g (3)
\]

Similarly, a force balance on a single particle in the bed yields

\[
\frac{n\Delta \rho g}{4f_f \varepsilon U_p^2 \rho_s} = \frac{n\Delta \rho g}{6} (4)
\]

In Equation (4), \(f_f\) is used in the left-hand term because the force balance applies to a single particle of a swarm so that the fluid is affected by the swarm and not just by the single particle.

A pressure drop expression that utilizes the single particle friction factor as well as the bed porosity is obtained by combining Equations (2), (3) and (4)

\[
\Delta p_s / Z = 3/4f_f ((1 - \varepsilon)/\varepsilon)^{4.65} \rho_s U_p^2 / d_n (5)
\]

Equation (5) should also be valid for a fixed bed since it represents a special case of a fluidized bed, one in which
the porosity does not depend on loading. Such is also the case for a packed column operating under dry (unirrigated) conditions. This can be demonstrated by comparison of Equation (5) with the large collection of pressure drop data presented by Coulson and Richardson. This comparison is shown in Figure 2 for beds of spheres. In addition, Rumpf and Gupte studied pressure drop in fixed beds with a systematic variation of porosity from 0.35 to 0.70, and found that the correction to the friction factor for a single particle was \((1 - \varepsilon)e^{-4.55}\) which compares favourably with the form of Equation (5).

The Ergun equation, generally accepted as descriptive of the pressure drop of a single phase fluid flowing through a fixed bed, is for the gas

\[
\Delta p_s/Z = f_s (1 - \varepsilon)^{1/2} \rho \sigma U^2 /d_p
\]  

The main difference between Equations (5) and (6) is the exponent on the porosity term. In the Ergun equation the porosity term results from an oversimplified model never validated experimentally, since porosity is a constant in a given packed bed. In Equation (5), however, the porosity term results from a large number of experiments in fluidized beds having a wide variation in porosity.

Because of the improved porosity term in Equation (5) the pressure drop in a bed of particles can be calculated from a knowledge of the friction factor of a single particle. Thus, there is no need for a friction factor of the bed. Figure 2 represents an example of how the data can be correlated by a relationship of the following type

\[
f_0 = C_1/Re_\varepsilon + C_2/(Re_\varepsilon)^{1/7} + C_3
\]

where the constants vary with packing type as shown in Table 1. Equation (5) should describe the dry pressure drop in a packed column given the appropriate single packing particle friction factor and the porosity of the dry bed. In doing so, it provides the basis for modelling of pressure drop under irrigated conditions.

### Pressure drop in an irrigated packing

The pressure drop of an irrigated bed is higher than that of a dry bed, as shown in Figure 3. This increase of pressure drop is caused by liquid being held up in the bed; this liquid changes the effective structure of the bed: porosity is decreased to \(E'\), particle diameter is increased to \(d'_p\), and friction factor changes to \(f'\).

The change in bed void fraction can be expressed as

\[
\varepsilon' = \varepsilon - h
\]

or

\[
\varepsilon' = \varepsilon (1 - h/\varepsilon) \tag{8}\]

where \(h\) is the operating hold-up (volume liquid/volume total bed). The change in particle diameter can be described by

\[
(1 - \varepsilon')/d'_p = (1 - \varepsilon)/d_p
\]

or

\[
d'_p = d_p (1 - \varepsilon (1 - h/\varepsilon)) \tag{9}\]

The friction factor for a single wet particle will be different from that of a dry particle since the actual gas Reynolds number depends on the actual wet particle diameter. Equation (7) can be simplified (see Appendix B) to

\[
f_0 \propto Re_\varepsilon \tag{10}\]

where

\[
\varepsilon = \frac{C_1}{Re_\varepsilon} - \frac{C_2}{(2Re_\varepsilon)^{1/7}}
\]

then the change in the friction factor will be

\[
f'_0 = f_0 \left(\frac{d'_p}{d_p}\right)^c \tag{11}\]

or

\[
f'_0 = f_0 \left\{ \frac{1 - \varepsilon}{\varepsilon} \left(1 - \frac{h}{\varepsilon}\right)^{1/3} \right\}
\]

Equations (8)-(11) describe the changes in the system that are caused by the presence of the liquid disregarding the effect of liquid drag on the gas flow. If these equations are substituted into Equation (5)

\[
\Delta p_{irr}/Z = 3/4f'_0 [(1 - \varepsilon)/\varepsilon]^{4.65} \rho \sigma U^2 /d'_p
\]  

\[
\varepsilon = 0.4
\]

\[
\text{Figure 2. Application of Equation (5) to friction factor data for beds of spheres as presented by Coulson and Richardson}^5
\]
The ratio of Equation (12) to Equation (5) gives, in combination with Equations (8), (9) and (11)

\[ \frac{\Delta p_{\text{ir}}}{\Delta p_d} = \left[ 1 - \kappa (1 - h/\eta) / (1 - \kappa) \right]^{0.45} \left( 1 - h/\eta \right)^{-0.14} \]

which describes the increase in pressure drop in an irrigated packing as a function of the dry packing void fraction and the liquid hold-up. This expression should be valid for any type of packing so long as the single particle dry friction factor can be described by Equation (10). Figure 4 shows how this expression describes various sets of experimental data for random and structured packings in the turbulent regime, where \( c = 0 \).

Comparison of Equation (13) with similar ones by Bemer and Kalis\(^1\), Billet and Mackowiak\(^2\), and Bravo \textit{et al.}\(^3\) clearly shows its advantages. First, there is no need for empirical packing correlation factors since the first term on the right-hand side of Equation (13) should account for all packing differences. Second, the influence of the effective void fraction on the pressure drop follows the same functionality for the wet and dry cases. Equation (13) should be valid below as well as above the loading point provided that the liquid hold-up is known or can be accurately predicted. The excellent fit of this model exhibited in Figure 4 demonstrates this fact; for all the points plotted there was a corresponding experimental liquid hold-up value. These experimental values

<table>
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<th>Packing</th>
<th>Type/size</th>
<th>( \varphi ) [m(^3)m(^{-1})]</th>
<th>( \varepsilon ) [-]</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
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Figure 3  Dry and wet pressure for 25 mm Bialecki rings². Air-water at 20°C; pressure = 1 bar; column diameter = 0.15 m

Figure 4  Validation of Equation (13), using different types of packings²

Figure 5  Hold-up of Bialecki rings, conditions as for Figure 3²

Figure 6 Correlation of liquid hold-up below the loading point (data by Billet¹⁰)

Figure 7  Shows that Equation (14) is applicable for liquid viscosities up to about 5 centipoises, based on the data of Buchanan¹¹. The influence of higher viscosities on hold-up is not fully accounted for. Nevertheless, most distillation, absorption and stripping applications of commercial importance exhibit viscosities in the range of applicability of Equation (14).

Still another effect that is not taken into account in Equation (14) is surface tension of the irrigating liquid. Mersmann and Deixler¹² developed a correlation for small Raschig rings that incorporates the effect of surface tension as indicated in Figure 8. It would appear that surface tension is important at low liquid loadings but

Liquid hold-up

The typical behaviour of liquid hold-up in a packed column for different liquid and gas loadings is shown in Figure 5 for a random packing. Below the loading point, the hold-up is a function only of the liquid rate; above the loading point the hold-up also depends on the gas rate. The region where there is an influence of gas rate is commonly known as the loading region.

Hold-up below the loading point

Numerous attempts have been made to describe the dependence of hold-up on liquid velocity below the loading point. Hold-up measurements by Billet¹⁰, for eight different packings, have been plotted in Figure 6 and may be correlated by

\[ h_o = 0.555 \cdot Fr_L^{1/3} \]  

where the Froude number is defined as

\[ Fr_L = \frac{U_L^2}{g \cdot \rho \cdot \mu} \]  

The correlation does not take into account any properties of the liquid and has been validated for air/water only. The definition of the Froude number includes the term \( \mu \) because it intuitively follows Equation (5). It was found that this definition provides an excellent correlation of the hold-up data.

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viscous forces are more important at higher loadings. It appears also that for a given loading, liquid hold-up increases with surface tension. This result is somewhat similar to findings of Bravo and Fair\textsuperscript{13} which suggests that the effective interfacial area for mass transfer in random packings increases with increasing surface tension.

**Hold-up above the loading point**

In this region liquid hold-up is affected by gas velocity and increases with gas rate at a constant liquid rate. The liquid in the packing is held back by friction forces imposed on it by the gas as well as by the static pressure gradient produced by the pressure drop. Buoyant forces also come into play in this region but are only significant in high pressure systems where the densities of gas and liquid are somewhat similar. The influence of gas velocity as well as the effect of the pressure gradient can be combined in a single dimensionless pressure drop term of the form \( \Delta p_{\text{irr}}/(Z_0 \rho_g) \). This term relates the actual pressure drop in the system to the maximum potential head available for liquid flow down the packing.

\[
\Delta p_{\text{irr}} = h_0 [1 + 20(\Delta p_{\text{irr}}/(Z_0 \rho_g))] \\
\]

Equation (16) is implicit in the irrigated pressure drop term and it also depends on an accurate value for the liquid hold-up (below the loading point) at the given liquid rate. It also provides a valuable tool for determining the capacity limits or flood point of a packed column, as shown below.

At the flood point the pressure drop increases infinitely with increasing gas load. If the gas load is represented by the dry pressure drop, the flooding condition is represented by

\[
\frac{\partial \Delta p_{\text{irr}}}{\partial \Delta p_d} = \infty \\
\]

or

\[
\frac{\partial \Delta p_d}{\partial \Delta p_{\text{irr}}} = 0 \\
\]

The influence of gas rate on hold-up in the loading region is complex, as indicated in Figure 5. However, if the hold-up is plotted versus pressure drop, as in Figure 9, its increase is uniform for all liquid loads. From Figure 9 the following relationship can be developed

\[
h = h_0 [1 + 20(\Delta p_{\text{irr}}/(Z_0 \rho_g))] \\
\]
Differentiation of Equation (16) then yields

$$\left( \frac{\Delta P_{\text{irr}}}{Z_{\text{p,irr}}} \right)^{2} = \frac{40 + e}{3} \frac{2 + e}{h_{0}} \left[ 1 - e + h_{0} \left[ 1 + 20 \left( \frac{\Delta P_{\text{irr}}}{Z_{\text{p,irr}}} \right)^{2} \right] \right] - \frac{186 h_{0}}{e} \frac{1}{h_{0} \left[ 1 + 20 \left( \frac{\Delta P_{\text{irr}}}{Z_{\text{p,irr}}} \right)^{2} \right]} = 0$$

(18)

The solution of this equation yields the pressure drop at the flood point. In most cases this pressure drop has a value between $\left[ \frac{\Delta P_{\text{irr}}}{Z_{\text{p,irr}}} \right]_{10} = 0.1-0.3$, which is in good agreement with practical experience.

The essential quantity for the calculation of the flood point is liquid hold-up. The data published thus far (mostly for air/water) are not sufficient to develop a correlation valid for all types of packing and all systems. In particular, experimental hold-up data are required for systems with low surface tensions and low viscosities.

**Validation of the model**

It seems clear that for the complex contacting mechanics in an irrigated packed column, the most meaningful method of validation is to compare the predicted parameters against those measured under test conditions. Liquid hold-up is not normally reported, and few reliable data are available; thus for this parameter the empirical correlation [Equation (14)] is used to support estimates of pressure drop and flooding.

Many pressure drop data have been reported, often for wide ranges of liquid and gas rates, and these permit comparisons between dry and irrigated pressure drops, as shown in Figure 3. When the loadings have been carried to high values, flooding conditions are obtainable from the same sets of data. The data bank that we have used for validation is shown in Table 1. It contains entries for structured as well as random packings. Data sources are given as part of the table.

For dry pressure drop, data were chosen carefully from graphed results unless specific values were reported.

Equations (15) and (16) were used to determine irrigated pressure drops. Comparisons between prediction and measurement were made in plots, such as those shown in Figures 10-12. Because of the huge amount of data, a single parity plot was not feasible.

Figures 10-12 demonstrate the ability of the model to predict the wet pressure drop for a variety of packing types. The comparison makes it clear that the pressure drop in the loading region can be predicted satisfactorily. Figures 13-16 are parity plots for flooding conditions. The agreement between experimental and model is satisfactory for all four data groups. The structured packings have larger deviations, particularly at combinations of high gas rates and low liquid rates. However, it is in this region that flooding velocities are difficult to measure and thus the basic data tend to be unreliable.

The validation of the model will continue as more data become available. Future adjustments may well be required. Still, the model currently represents the best
available approach for estimating pressure drop in gas-liquid packed columns, particularly those which operate on systems other than air-water.

References

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Appendix A

Example calculation

Calculate the pressure drop and flood point for an irrigated packing under the following conditions:

- Gas velocity: \( U_g = 0.4 \text{ m s}^{-1} \)
- Liquid loading: \( U_l = 5 \times 10^{-3} \text{ m}^3 \text{ (m}^3 \text{ s})^{-1} \)

Properties:
- Gas density = 5 kg m\(^{-3}\)
- Liquid density = 1200 kg m\(^{-3}\)
- Kinematic viscosity of gas = 10\(^{-5}\) m\(^2\) s\(^{-1}\)
- Kinematic viscosity of liquid = 2 \times 10\(^{-6}\) m\(^2\) s\(^{-1}\)

Packing: Berl saddles, 25 mm (\( \alpha = 260 \text{ m}^{-1} \); \( E = 0.68 \))

1 Calculation of the dry pressure drop

(a) Equivalent diameter of the packing

\[
d_p = \frac{6(1 - \varepsilon)}{a} = \frac{6(1 - 0.68)}{260} = 7.39 \times 10^{-3} \text{ m}
\]

(b) Friction factor for a single particle [Equation (7)]

\[
f_0 = \frac{C_1}{Re_g} + \frac{C_2}{Re_g^{1/2}} + C_3
\]

where

\[
Re_g = \frac{0.4 \times 7.39 \times 10^{-3}}{10^{-5}} = 295.4
\]

Constants for the packing (Table 1)

\[
C_1 = 32, \quad C_2 = 7, \quad C_3 = 1
\]

\[
f_0 = \frac{32}{295.4} + \frac{7}{(295.4)^{1/2}} = 1.5156
\]

(c) Dry pressure drop [Equation (5)]

\[
\Delta P_{dry} = \frac{3}{4} f_0 \left( \frac{1 - \varepsilon}{\varepsilon} \right)^{1/3} \rho_g Z \frac{U_g^2}{d_p}
\]

\[
= \frac{3}{4} \left( 1.5156 \right) \left( 1 - 0.68 \right) \left( 0.68^{1/3} \right) \left( 7.39 \times 10^{-3} \right)^{(0.4)^2}
\]

\[
= 236.81 \text{ N m}^{-2} \text{ per metre of packed height}
\]

2 Pressure drop for irrigated packing

(a) Liquid hold-up, below the loading point [Equation (14)]

\[
h_0 = 0.555 \frac{F_{L0}}{Re_g^{1/3}}
\]

\[
= 0.555 \left( \left( 5 \times 10^{-3} \right)^2 \left( 260 \right) \right)^{1/3}
\]

\[
= 0.088 \text{ m}^3 \text{ m}^{-3}
\]

where

\[
F_{L0} = \frac{U_l^2}{g \varepsilon^{4.65}}
\]

(b) Exponent \( c \) for calculation of the irrigated pressure drop [Equation (10)]

\[
c = \frac{\delta \ln(f_0)}{\delta \ln(Re_g)}
\]

\[
= \frac{-C_1/Re_g - C_2/(2 Re_g^{1/2})}{f_0}
\]

\[
= (32/295.2) - [7/2(295.2)^{1/2}]^{-1}
\]

\[
= -0.20584
\]

(c) Irrigated pressure drop. The irrigated pressure drop is obtained by iterative calculations. As a starting point, assume that the irrigated pressure is equal to the dry pressure drop. Equation (16) is used:

\[
\frac{\Delta P_{irr}}{\rho_g Z} = \frac{\Delta P_{dry}}{\rho_g Z} \times \left\{ 1 - \varepsilon \left[ 1 - \frac{h_0}{\varepsilon} \left[ 1 + 20 \left( \frac{\Delta P_{irr}}{\rho_g Z} \right)^{2} \right]^{2} \right] \right\}^{1/4.65}
\]

Results of the iterative calculations

\[
\frac{\Delta P_{irr}}{\rho_g Z} = 0.0459
\]

\[
\frac{\Delta P_{irr}}{\rho_g Z} = \frac{\Delta P_{irr}}{\rho_g Z} \cdot \frac{539.81 \text{ N m}^{-2} \text{ m}^{-1}}{	ext{per metre of packed height}}
\]

The pressure drop of the gas, for the given liquid and gas loadings, is 539.81 N m\(^{-2}\) per metre of packed height.
Flood point [Equation (18)]. The flood point is calculated from Equation (18)

\[
\frac{1}{\Delta p_{\text{m}} / \rho_1 g Z} - \frac{40 \left(2 + c\right) \Delta p_{\text{m}} / \rho_1 g Z}{1 - \varepsilon + h_0 \left[1 + 20 \left(\Delta p_{\text{m}} / \rho_1 g Z\right)^2\right]} - \frac{186 h_0}{\varepsilon - h_0 \left[1 + 20 \left(\Delta p_{\text{m}} / \rho_1 g Z\right)^2\right]} = 0
\]

The procedure for calculating the flood point is as follows:
(a) assume a gas rate;
(b) calculate the dry pressure drop;
(c) for the same gas rate and a fixed liquid rate, calculate the irrigated pressure drop; and
(d) using Equation (18), check to see whether the assumed condition gives closure. If not, assume a new gas rate and repeat the calculations.

**Results**

\[U_{G, \text{flooding}} = 0.64 \text{ m s}^{-1}\] (for \[U_L = 5 \times 10^{-3} \text{ m}^3 \text{ m}^{-1}\])

\[\Delta p_{\text{d}, \text{flooding}} = 555.23 \text{ N m}^{-2} \text{ m}^{-1}\]

\[\Delta p_{\text{lin}, \text{flooding}} = 1976.52 \text{ N m}^{-2} \text{ m}^{-1}\]

Thus, the design gas rate is \(0.4/0.64 = 0.625 = 62.5\%\) of flooding.

**Appendix B**

**Derivation of Equation (10)**

We have defined the friction factor, \(f_0\), such that

\[f_0 = \frac{C_1}{Re} + \frac{C_2}{Re^{\alpha/2}} + C_3\]  \hspace{1cm} (1)

We propose that

\[f_0 \propto Re^c\]

or

\[f_0 = A Re^c\]  \hspace{1cm} (2)

Taking logarithms

\[\ln f_0 - \ln A + c \ln Re\]  \hspace{1cm} (3)

Taking the derivative of Equation (3)

\[
\frac{1}{f_0} \frac{df_0}{d \ln Re} = \frac{d \ln f_0}{d \ln Re} = c = \frac{\frac{df_0}{f_0}}{\frac{d \ln Re}{d Re}}
\]

Simplifying the differentials in Equation (4)

\[
\frac{1}{f_0} \frac{df_0}{d Re} = \frac{d \ln f_0}{d \ln Re} = c = \frac{Re}{f_0} \frac{df_0}{d Re}
\]

Differentiating Equation (1) with respect to \(Re\)

\[
\frac{d f_0}{d Re} = \frac{-C_1}{Re^2} - \frac{1}{2 Re^{3/2}}
\]

Substituting Equation (6) into Equation (5)

\[
c = \frac{Re}{f_0} \left[-\frac{C_1}{Re^2} - \frac{1}{2 Re^{3/2}}\right]
\]

or

\[
c = -\frac{1}{f_0} \left[\frac{C_1}{Re} + \frac{1}{2 Re^{1/2}}\right]
\]

Equation (7a) is the same as Equation (10) in the paper. Thus, if Equations (1) and (2) are true, then Equation (7a) is true.