Journal of Chromatography A, 1218 (2011) 6038–6043

Contents lists available at ScienceDirect

Journal of Chromatography A

journal homepage: www.elsevier.com/locate/chroma

Improved g-level calculations for coil planet centrifuges

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ARTICLE INFO

Article history:
Available online 22 June 2011

Keywords:
g-Level
Coil planet centrifuge
Counter current chromatography
Centrifugal partition chromatography
Non-synchronous

ABSTRACT

Calculation of the g-level is often used to compare CCC centrifuges, either against each other or to allow for comparison with other centrifugal techniques. This study shows the limitations of calculating the g-level in the traditional way. Traditional g-level calculations produce a constant value which does not accurately reflect the dynamics of the coil planet centrifuge. This work has led to a new equation which can be used to determine the improved non-dimensional values. The new equations describe the fluctuating radial and tangential g-level associated with CCC centrifuges and the mean radial g-level value. The latter has been found to be significantly different than that determined by the traditional equation. This new equation will give a better understanding of forces experienced by sample components and allows for more accurate comparison between centrifuges. Although the new equation is far better than the traditional equation for comparing different types of centrifuges, other factors such as the mixing regime may need to be considered to improve the comparison further.

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1. Introduction

Counter-current chromatography (CCC) is a liquid–liquid extraction technique where two immiscible liquid phases are used to perform a separation [1]. One of the two phases is retained in the column while the other, the "mobile" phase, is pumped through the column transporting the sample and the separated components. The column consists of a length of coiled tubing wound on a drum (sometimes also referred to as bobbin) and is mounted on a planetary centrifuge. This configuration is referred to as the coil planet centrifuge. The so-called "stationary" phase is retained due to the rotation of the column. The rotation of the column creates two forces on the fluids inside the column. The first force is the Archimedean screw force which is mainly responsible for the pumping action of the spinning column [2] and the second force is the centrifugal force which is mainly responsible for the mixing and settling of the two immiscible phases. The resulting continuous mixing and settling steps are responsible for the separation process that allows the isolation of individual components in the mixture. The efficiency of the separation is dependent on a number of factors including the physical properties of the phase system, such as the density difference, viscosity and interfacial tension, as well as machine specifics such as the β-value and the rotational speed exerting the mixing and settling "forces". Depending on the physical properties, phase systems need a different level of mixing and settling. The most commonly used and commercially available CCC centrifuge is the J-type centrifuge with a 1:1 drive ratio (Pr = 1, where Pr is the ratio between the column speed and rotor speed). For the J-type CCC centrifuge the only variables available for altering the separation efficiency are the phase system properties, flow rate and centrifuge specifics (like rotational speed, column size and configuration). Recently a new Non-synchronous CCC (NSCCC) centrifuge, built specifically to allow for the separation of delicate sample material, was tested with an aqueous-organic phase system [3]. The results have shown a step change in efficiency when the drive ratio (Pr) is changed compared with the J-type centrifuge [4].

Understanding the g-level values acting on the fluids in the column due to the rotations may provide a better understanding of the mixing and settling efficiency inside the column. The g-level value of a rotating point is the acceleration produced by the rotation in the radial direction (radial acceleration) divided by the gravitational acceleration. The acceleration produced due to the motion in a NSCCC centrifuge has previously been analysed [5]. However, only the total acceleration from the acceleration in the x- and y-direction were described and the analysis of the acceleration in the radial and tangential direction was omitted. The analysis of the velocities and accelerations was recently extended by Wood during a study on critical β-values in coil planet centrifuges [6]. Wood hypothesised that when the Pr in NSCCC centrifuges changes, the β-values at which the mixing regime transitions from cascade mixing to wave mixing, also changes. These transition points were identified as two critical β-values that are only dependant on the Pr ratio.

Currently for J-type machines (with a 1:1 ratio of rotor and column speed) the g-level is calculated for the centre of the column [7] which is a valid comparison between J-type machines of the same β-value [8]. However, even in this case it needs to be recognised

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doi:10.1016/j.chroma.2011.06.059

that the g-level is calculated for the centre of the coiled column which does not coincide with the actual g-level value experienced within the column. The traditional equation is not adequate to allow for comparison between centrifuges of the same type (with the same drive ratio, for example the J-type centrifuge,) with different β-values or between centrifuges of different types of design. The traditional equation (Eq. (1) below) does not include the radius of the column (r) or the rotational speed of the column (φ). To be able to compare between all types of coil planet centrifuges an understanding of the correct g-level values, the types of mixing likely to occur within the column and which phase will occupy the head of the column is required. The purpose of this study is to provide a new set of equations for the g-level value to aid with the comparison of CCC centrifuges. This work builds on previous numerical modelling work using computational fluid dynamics [9].

2. Theory

2.1. Traditional (rotor) g-level calculation

The g-level for a J-type centrifuge is currently defined as follows:

$$\text{g-Level} = \frac{R\omega^2}{9.807} \tag{1}$$

where R is the radius of the rotor in meters (m), ω is the rotational speed of the rotor in radians (rotations) per second (rad s^{-1}) and 9.807 is the gravitational acceleration in meters per second square (m s^{-2}) [7]. This equation is also used to calculate the g-level obtained in centrifuges and centrifugal partition chromatography (CPC) [10].

In Fig. 1, the relationship between the rotor angle (θ) and the rotational speed of the rotor is $\theta = \omega t$. The traditional (rotor) g-level equation (Eq. (1)) is derived from the displacement of one point on the rotor (or the centre of the column, C) as shown below.

$$x_C = R\cos(\theta) = R\cos(\omega t) \tag{2}$$

$$y_C = R\sin(\theta) = R\sin(\omega t) \tag{3}$$

The second derivative of the position equations (Eqs. (2) and (3)) gives the acceleration in the x- and y-direction, resulting in:

$$a_{Cx} = \frac{d^2x_C}{dt^2} = -R\omega^2\cos(\omega t) \tag{4}$$

$$a_{Cy} = \frac{d^2y_C}{dt^2} = -R\omega^2\sin(\omega t) \tag{5}$$

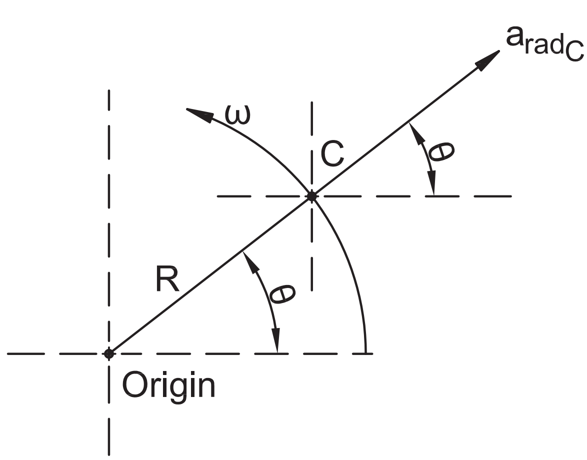

Fig. 1. Diagram of the motion of a centrifuge rotor with radius (R), displacement angle (θ) and rotational speed (ω). Point C indicates where the centre of the column is in the coil planet centrifuge. The radial acceleration (a_{rad_C}) has the same angle as the rotor displacement.

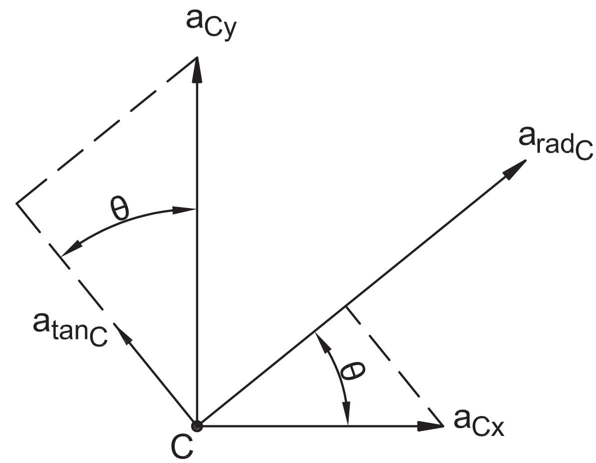

Fig. 2. Diagram of the acceleration of one point (C) on the rotor in the x- and y-direction (a_{Cx} and a_{Cy}) and how the radial and tangential acceleration can be derived.

These accelerations can then be used to calculate the acceleration in the radial and tangential direction.

Fig. 2 shows how the radial and tangential accelerations are translated from the acceleration in the x- and y-direction using the angle of rotation (θ). The acceleration in the x- and y-direction can be resolved into the radial and tangential acceleration as is shown in the following set of equations:

$$a_{\text{rad}_C} = a_{Cx}\cos(\theta) + a_{Cy}\sin(\theta) \tag{6}$$

$$a_{\tan_C} = -a_{Cx}\sin(\theta) + a_{Cy}\cos(\theta) \tag{7}$$

For the centrifuge rotor (and the centre of the column) the radial acceleration equation becomes as follows:

$$a_{\text{rad}_C} = a_{Cx}\cos(\omega t) + a_{Cy}\sin(\omega t) \tag{8}$$

$$a_{\text{rad}_C} = -\omega^2R\cos^2(\omega t) - \omega^2R\sin^2(\omega t) \tag{9}$$

$$a_{\text{rad}_C} = -\omega^2R(\cos^2(\omega t) + \sin^2(\omega t)) \tag{10}$$

Applying the geometry rule $\cos^2(\omega t) + \sin^2(\omega t) = 1$ to Eq. (10) leads to the equation for the acceleration in the radial direction for one point on the rotor:

$$a_{\text{rad}_C} = -\omega^2R \tag{11}$$

The traditional rotor g-level (Eq. (1)) is then obtained by dividing this equation by the gravitational acceleration (g). The negative sign in Eq. (11) shows that the radial acceleration (a_{rad_C}) acts in the opposite direction to that shown in Fig. 1, i.e., towards the centre of rotation. The original g-level calculation (Eq. (1)) was to compare the acceleration generated on a centrifuge with the acceleration due to Earth's gravity. This comparison is only in terms of magnitude and therefore the sense of direction (towards the centre of rotation or towards the periphery) is not important.

The tangential acceleration for the centrifuge rotor (and the centre of the column) is zero as is shown in the following equations:

$$a_{\tan_C} = -a_{Cx}\sin(\omega t) + a_{Cy}\cos(\omega t) \tag{12}$$

$$a_{\tan_C} = R\omega^2\cos(\omega t)\sin(\omega t) - R\omega^2\sin(\omega t)\cos(\omega t) \tag{13}$$

$$a_{\tan_C} = 0 \tag{14}$$

2.2. Derivation of a new g-level equation for coil planet centrifuges

As shown in the previous section the rotor g-level equation (Eq. (1)) only considers the rotor radius and rotational speed. In coil

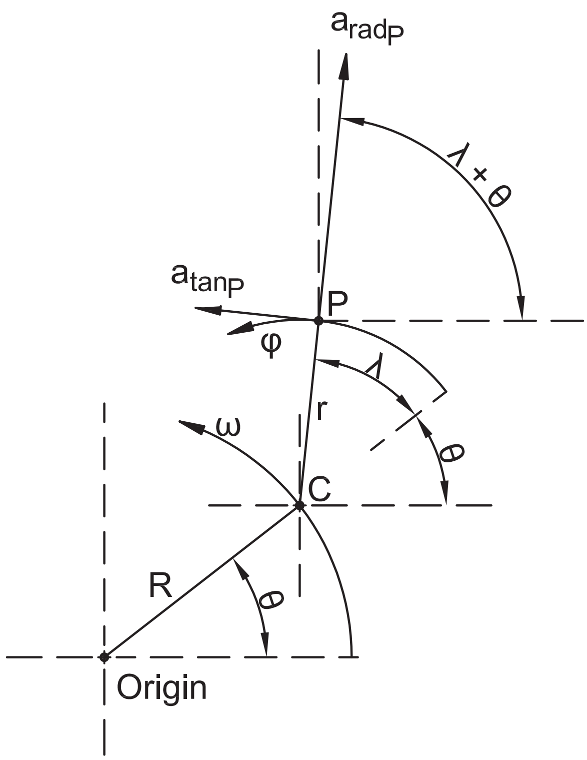

Fig. 3. Diagram of the motion of the non-synchronous centrifuge with the angles and rotational speed for both the rotor (θ, ω) and the column (λ, φ). Point P indicates a point on the periphery of the column. The radial and tangential accelerations (a_{rad_P} and $a_{\tan_P}$, respectively) are calculated for this point.

planet centrifuges both the rotor and the column rotate each having its own radius. The acceleration into the radial and tangential direction for a point (P) on the column of a coil planet centrifuge is derived as shown in Fig. 3.

Fig. 3 shows the displacement of a point on the periphery of the column (P) and the angles and rotational speeds of both the rotor and the column. While $\theta = \omega t$ is the relationship between the angle and the rotational speed of the rotor, $\lambda = \varphi t$ is the relationship between the angle (λ) and rotational speed (φ) of the column.

Displacement in the x- and y-direction for the non-synchronous centrifuge is as follows [6]:

$$x_P = R\cos(\theta) + r\cos(\lambda+\theta) \quad (15)$$

$$x_P = R\cos(\omega t) + r\cos((\varphi+\omega)t) \quad (16)$$

$$y_P = R\sin(\theta) + r\sin(\lambda+\theta) \quad (17)$$

$$y_P = R\sin(\omega t) + r\sin((\varphi+\omega)t) \quad (18)$$

where r is the radius of the column in meters (m). The accelerations in the x- and y-direction for the non-synchronous centrifuge are the respective second derivatives with respect to time:

$$a_{Px} = \frac{d^2x_P}{dt^2} = -R\omega^2\cos(\omega t) - r(\varphi+\omega)^2\cos((\varphi+\omega)t) \quad (19)$$

$$a_{Py} = \frac{d^2y_P}{dt^2} = -R\omega^2\sin(\omega t) - r(\varphi+\omega)^2\sin((\varphi+\omega)t) \quad (20)$$

The accelerations in the x- and y-direction for point P can be resolved into the radial and tangential accelerations as was shown for the accelerations on point C in Fig. 2. This was also shown by Wood [6] and the resulting radial and tangential accelerations are as follows:

$$a_{\mathrm{rad}_P} = -R(\omega^2(\cos(\varphi t)) + \beta(\varphi+\omega)^2) \quad (21)$$

$$a_{\tan_P} = R\omega^2(\sin(\varphi t)) \quad (22)$$

where β is the β-value which is the ratio between the column and rotor radii.

Both equations were recently published by Ignatova et al. [4]. In the radial acceleration equation $\cos(\varphi t)$ will fluctuate between -1 and +1, this leads to an acceleration pattern in form of a cosine function with $R\cdot\omega^2$ as its amplitude, the same as the radial acceleration of the centre of the column. The maximum and minimum radial accelerations can be found for $\cos(\varphi t) = 1$ and $\cos(\varphi t) = -1$ and, respectively. The mean radial acceleration can then be obtained for $\cos(\varphi t) = 0$. Hence the following equation set gives the maximum, minimum and mean radial acceleration.

$$Max\_a_{\mathrm{rad}_P} = -R(\beta(\varphi+\omega)^2 + \omega^2) \quad (23)$$

$$Min\_a_{\mathrm{rad}_P} = -R(\beta(\varphi+\omega)^2 - (\omega^2)) \quad (24)$$

$$Mean\_a_{\mathrm{rad}_P} = -R(\beta(\varphi+\omega)^2) \quad (25)$$

From the radial acceleration equations derived above the g-level values can be calculated using the gravitational acceleration. The g-level equations become as follows:

$$g_{\mathrm{rad}_P} = \frac{R(\omega^2(\cos(\varphi t)) + \beta(\varphi+\omega)^2)}{9.807} \quad (26)$$

$$Max\_g_{\mathrm{rad}_P} = \frac{R(\beta(\varphi+\omega)^2 + \omega^2)}{9.807} \quad (27)$$

$$Min\_g_{\mathrm{rad}_P} = \frac{R(\beta(\varphi+\omega)^2 - \omega^2)}{9.807} \quad (28)$$

$$Mean\_g_{\mathrm{rad}_P} = \frac{R(\beta(\varphi+\omega)^2)}{9.807} \quad (29)$$

In the tangential acceleration equation $\sin(\varphi t)$ will fluctuate between 1 and -1. This sin function will have an amplitude of $R\cdot\omega^2$ and fluctuates around zero. This means that the maximum tangential acceleration of point P on the column equals to the radial acceleration of the centre of the column point C (Eq. (11)). To be able to evaluate the tangential acceleration with the radial acceleration and put them together in one graph the tangential acceleration is also divided by the gravitational acceleration. This gives the following equation:

$$g_{\tan_P} = -\frac{R\omega^2(\sin(\varphi t))}{9.807} \quad (30)$$

To visualise the g-level values of coil planet centrifuges a Java Applet model was generated which is available online [11]. The described equations can also be used in a Microsoft Excel spreadsheet or other mathematical software. An example of the g-level calculations (prepared in a Microsoft Excel spreadsheet) for a specific centrifuge configuration is shown in Fig. 4. The Java Applet model generates a similar graph as a result of user input. The figure shows the fluctuating radial and tangential g-levels, the mean radial g-level values and the traditionally calculated rotor g-level. The g-levels are shown against the time and the angular position of the column (on the x-axis). Fig. 4 shows that the radial and tangential accelerations experienced at point P on the column vary cyclically with the same frequency as the rotational speed of the column.

When the angular velocity for the rotor and the column are the same ($\varphi = \omega$), which corresponds to a drive ratio of 1, the motion of the NSCCC coil planet centrifuge becomes that of a J-type machine. When the angular velocities are the opposite ($\varphi = -\omega$ or $-\varphi = \omega$), and the drive ratio is -1, the motion of the NSCCC centrifuge becomes that of an I-type machine. The improved g-level equation (Eq. (26)) and the mean, maximum and minimum g-level value equations (Eqs. (27)–(29)) are valid for all situations except one. When the

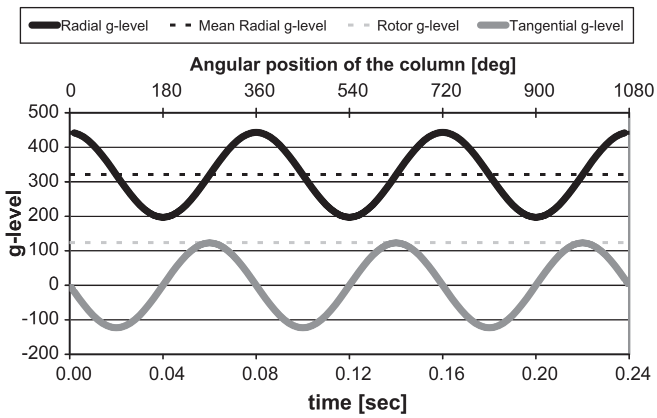

Fig. 4. Analysis of the g-level Eqs. (1), (26), (29) and (30). The variables used in the equations are: β-value = 0.85, R = 0.11 m, ω = 1000 rpm and φ = 750 rpm (which gives Pr = 0.75).

angular velocity of the column (φ) is 0 (as was used in [4]) the radial g-level value becomes a constant which differs from the mean radial g-level value (Eq. (29)). This means that when $\varphi = 0$ the mean, max and min g-level value equations are no longer valid but the real g-level value (Eq. (26)) still holds true.

3. Results and discussion

3.1. J-type centrifuge comparisons

3.1.1. J-type centrifuges with same β-values

The traditional (rotor) g-level equation (Eq. (1)) is applicable for the comparison of J-type centrifuges of matching β-values despite the fact that the actual g-level experienced by the fluids and components in the column is significantly higher. During a study on scale-up Ignatova et al. [8] compared three different types of J-type centrifuges of same β-value (0.85). These centrifuges were the Dynamic Extractions (DE) Mini (R = 0.05), the DE Midi (R = 0.11) and the DE Maxi (R = 0.30). The rotor g-level was calculated in the traditional way (Eq. (1)) with the derived value being used to determine the different rotational speeds that would result in equal g-levels in each of the three centrifuges. Because the β-values of the three centrifuges are the same one can predict the rotational speeds at a constant g-level using the traditional calculation (Eq. (1)) or the new mean g-level value equation (Eq. (29)). This is demonstrated in Fig. 5 where the rotor g-level at the centre of the column and the improved mean radial g-level value of the three types of J-type centrifuges are shown against the rotational speed.

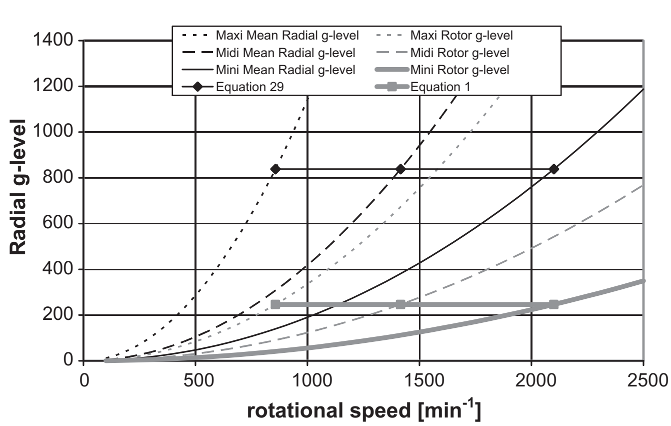

Fig. 5. Comparison of rotor g-level and mean radial g-level values for a single point on the column for three J-type centrifuges of different sizes but identical β-value.

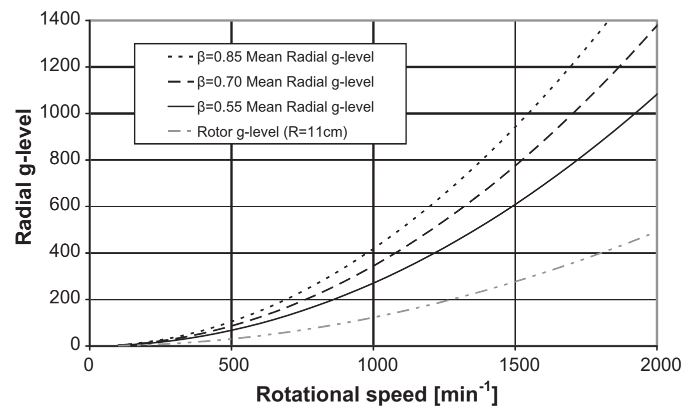

Fig. 6. Comparison of three β-values (0.55, 0.70 and 0.85) for the same J-type centrifuge with constant rotor radius (R = 0.11 m).

In Fig. 5 two lines are drawn through points with the same mean radial g-level values. The upper line represents the g-level values calculated with the new, improved mean radial g-level equation (Eq. (29)) while the lower line corresponds to the traditional rotor g-levels as calculated with Eq. (1). These two parallel lines show that the difference between the rotor g-level and the mean radial g-level value is the same for all three machine sizes shown. However, this is only valid because the J-type machines used in this comparison have the same β-value.

3.1.2. J-type centrifuges with different β-values

Although the traditional rotor equation permits comparison of different sized J-type centrifuges of same β-value this does not hold when β-values differ. Fig. 6 shows the rotor g-level at the centre of the column and the mean radial g-level value for a single point on the column for three different β-values (0.55, 0.70 and 0.85) at the same rotor radius (R = 0.11 m). As expected the values for the centre of the column are the same for all the three β-values. In Fig. 6 it can be seen that at a particular rotational speed the centrifuge with the smallest β-value has the smallest mean radial g-level value and that this g-level value increases in a linear fashion when the β-value increases. This is shown in Fig. 7 where the mean radial g-level is plotted against the β-value for five rotational speeds on the same J-type centrifuge. To achieve the same mean radial g-level value for a set of centrifuges of different β-values and same rotor radius, the centrifuge with the smallest β-value will need to be rotated the fastest while the centrifuge with the highest can be rotated the slowest. Critical β-values will need to be taken into consideration

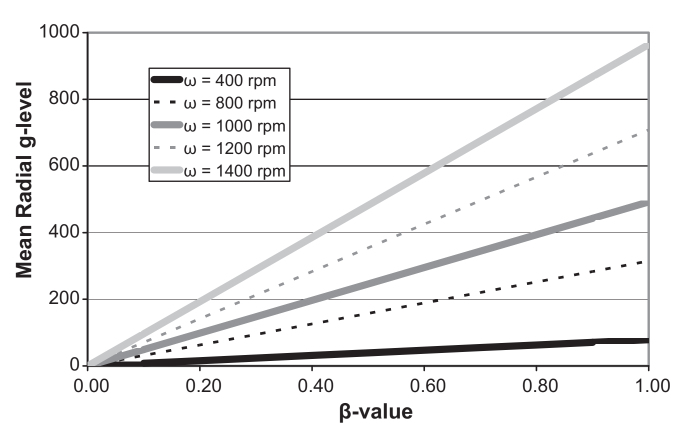

Fig. 7. The mean radial g-level increases linearly with increasing β-values for five rotational speeds (400, 800, 1000, 1200 and 1400 rpm) for the same J-type centrifuge with constant rotor radius (R = 0.11 m).

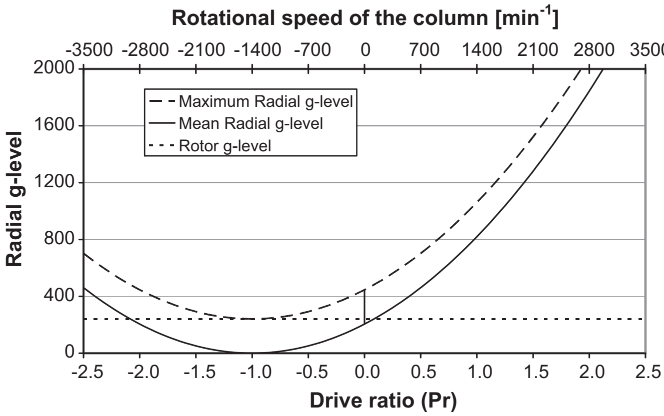

Fig. 8. Mean and maximum radial g-level values for $\omega = 1400$ rpm, β-value = 0.85 and $R = 0.11$ m with drive ratios varying from −2.5 to 2.5 which corresponds to a range for φ from −3500 rpm to 3500 rpm.

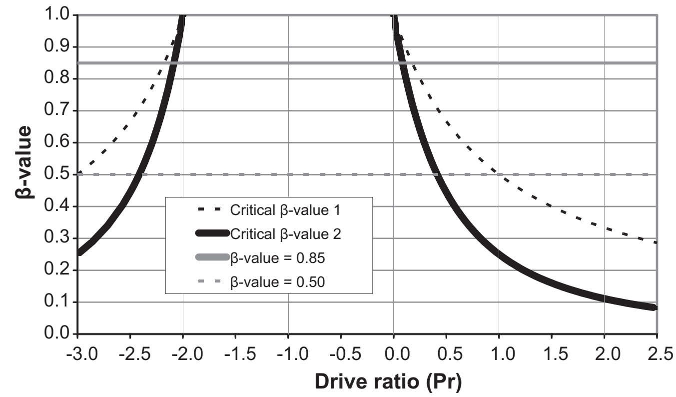

Fig. 9. The critical β-values against the drive ratio (Pr) [6]. Two β-values are also drawn in the graph to show the minimum and maximum β-value for a DE Midi centrifuge and how this crosses the critical β-values.

when comparing J-type centrifuges (Pr = 1) with different β-values because the mixing regime may change when the β-value becomes lower than 0.5 [6].

3.2. Non-synchronous centrifuge comparison

Knowledge of the accurate g-level values as experienced by the sample is of utmost importance when developing more flexible machinery to cater for the separation of fragile components like cells and proteins [10,12]. Therefore, the maximum radial g-level, the mean radial g-level and the rotor g-level values were calculated for a range of drive ratios for NSCCCs. Fig. 8 shows the result for the traditional rotor calculation (Eq. (1)) compared with the mean and maximum radial g-level values calculated by the new equations (Eqs. (27) and (29)). The importance of the new equation is clearly seen because the traditional equation gives a constant g-level value throughout all the different drive ratios but the actual radial g-level value on the column varies enormously. The graph shows that the traditional rotor equation only matches the maximum radial g-level value when the drive ratio is at −1 ($\omega = -\varphi$). At all other drive ratios the maximum radial g-level value is higher than the rotor g-level and the difference between the values increases as the drive ratio moves further away from −1. The true mean radial g-level value also changes in response to different drive ratios in line with the maximum radial g-level value but lower, so that at drive ratio −1, the mean radial g-level value reaches zero. The point where the mean radial g-level value becomes larger than the rotor g-level depends on the β-value of the centrifuge. The critical β-values, as discussed by Wood [6], may need to be taken into consideration when comparing NSCCC centrifuges at different drive ratios. One may need to determine the type of mixing and which phase occupies the head of the column together with the g-levels in the column to ensure a fair comparison. Fig. 9 shows the critical β-values as calculated from Wood's equations [6]. The two β-values (0.50 and 0.85) are the minimum and maximum β-values on a commercially available DE Midi centrifuge. According to Wood's hypothesis wave mixing occurs above the black dotted lines (critical β-value 1), cascade mixing occurs beneath and between the black solid lines (critical β-value 2) and "enhanced wave mixing" occurs between the black solid and dotted lines. This would mean that for a NSCCC centrifuge with a DE Midi rotor and column (β-value range from 0.50 to 0.85) wave mixing occurs below Pr = −3 and above Pr = 1, cascade mixing occurs between Pr = −2 and Pr = 0 and "enhanced wave mixing" occurs from Pr = −3 to Pr = −2 and Pr = 0 and Pr = 1. The type of mixing should be taken into account when comparing different types of centrifuges.

For the special case of a drive ratio of 0 ($\varphi = 0$) the radial g-level value is constant as the planetary drive centrifuge with the column acts as a simple centrifuge. This means that there is no fluctuation in the radial g-level values and therefore the mean, minimum and maximum radial g-level values are the same and can only be calculated using Eq. (26). The vertical line added at the Pr = 0 value in Fig. 8 shows where this occurs.

The relationship between the radial g-level values and the drive ratio can be described when the definition for the drive ratio (Pr) is combined with the mean and maximum radial g-level value Eqs. (27) and (29) thus eliminating the term for the column speed (φ). The resulting equations can be written as second order polynomial equations ($a \cdot \mathrm{Pr}^2 + b \cdot \mathrm{Pr} + c$) where for the mean radial g-level values the constants a and c are the mean radial g-level values with $\varphi = 0$ and b is two times the mean radial g-level value with $\varphi = 0$. For the maximum radial g-level values relationship a and b are the same as for the mean radial g-level values relationship but c is the maximum radial g-level value with $\varphi = 0$.

In Ignatova et al. [4] six different drive ratios (between −1 and 1.5) were tested for retention and for separation efficiency all at a constant rotor speed of 800 rpm. Fig. 10 shows the locus and radial g-level values for three of the drive ratios studied in [4]. The highest retention of the stationary phase was observed at a drive ratio of −0.6 (Fig. 10a). A step change in separation efficiency was detected around the ratio of 0.7 (Fig. 10b) compared to the traditional synchronous centrifuge (Pr = 1, Fig. 10c). Whether the experimentally observed improvement is due to the lower g-level value or the increase in the time lag between the mixing and settling steps or the change in mixing regime due to the change in drive ratio is currently unknown and is something which needs to be investigated further. Fig. 10 also shows that the rotational speed is directly related to the cyclic (driving) frequency of the g-level of the point on the column. As the rotational speed is increased (both for the rotor and the column) the cyclic frequency of the g-level fluctuations also increases. The rotor and radial g-level values corresponding to all eight drive ratios tested are listed in Table 1. For the rotor speed used ($\omega = 800$ rpm) it can clearly be seen that for a drive ratio of 1 the mean radial g-level (Eq. (29) gives 268 g at 800 rpm) is 3.4 times higher than the rotor g-level value (Eq. (1) gives 79 g at 800 rpm). The difference between the two calculated values stays the same regardless of the rotational speed. Furthermore, at the more efficient drive ratio, as established experimentally (Pr = 0.7), the mean radial g-level value (186 g at 800 rpm) is only 70% of the mean radial g-level value at a drive ratio of 1 (268 g at 800 rpm) as is the case for a synchronous CCC centrifuge.

Table 1
Rotor, maximum and mean g-levels for three different rotor speeds and six different drive ratios in reference to [4] (R = 0.11 m, β = 0.85).

Pr	ω = 800 rpm			ω = 1000 rpm			ω = 1400 rpm		
	Rotor	Max	Mean	Rotor	Max	Mean	Rotor	Max	Mean
	g-level	Radial g-level		g-level	Radial g-level		g-level	Radial g-level	
−1	79	79	0	123	123	0	241	241	0
−0.6	79	89	11	123	140	17	241	274	33
0	79	146	67	123	228	105	241	446	205
0.3	79	192	113	123	300	177	241	587	346
0.5	79	229	151	123	358	235	241	702	461
0.7	79	272	193	123	425	302	241	833	592
1	79	346	268	123	541	418	241	1061	820
1.5	79	497	418	123	776	653	241	1522	1281

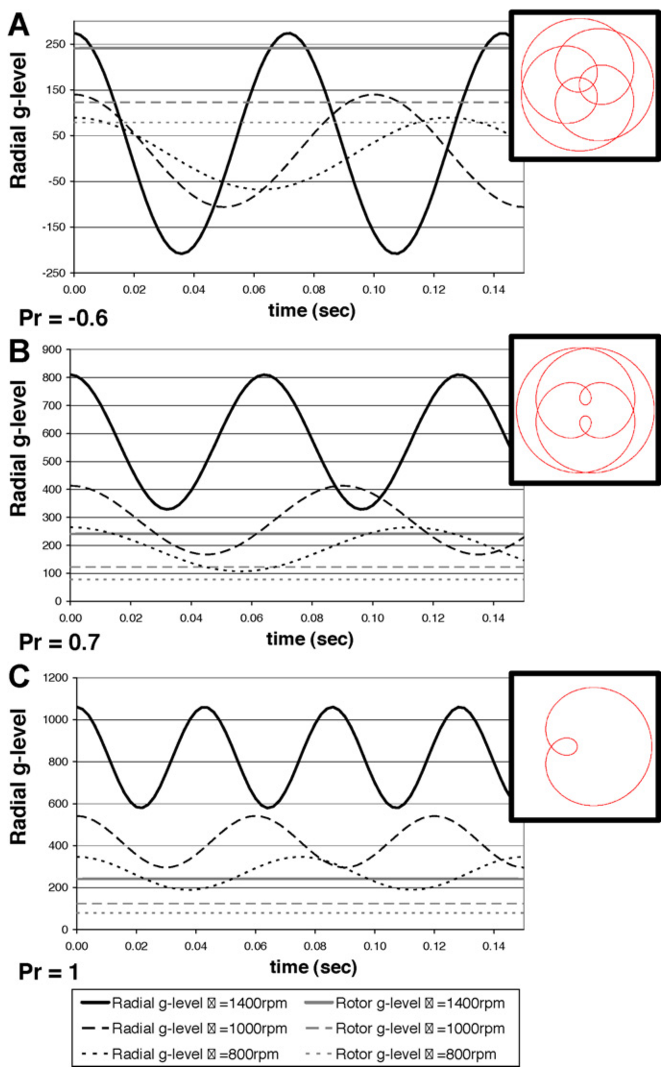

Fig. 10. Locus and radial g-level values for three different drive ratios: (A) Pr = −0.6, (B) Pr = 0.7 and (C) Pr = 1.

4. Conclusions

The traditional rotor g-level equation is not adequate to compare between the same type centrifuges with different β-values or between different types of centrifuges. It does not give an accurate picture of the forces acting on the phase systems and sample components in the CCC column. This is particularly important for NSCCC centrifuges where the true g-level values and, importantly, the maximum radial g-level values are much greater than the traditionally calculated rotor g-level at all except one of the drive ratios that could be used.

We can conclude that the original equation for the rotor g-level (Eq. (1)) can be used when comparing different J-type centrifuges with the same β-value, but the g-levels calculated this way are not representative for the actual g-level value or even the mean radial g-level value that the particles and fluids in the coiled column experience. It is therefore recommended to use the mean radial g-level equation when comparing different machines. When comparing J-type centrifuges of different β-values, the traditional equation does not give an accurate result and therefore the new, improved mean radial g-level value equation must be used and the type of mixing may need to be considered.

The improved way of calculating the g-level value shown in this work is a more accurate representation of the g-levels the column experiences when it is being rotated within the coil planet centrifuge. This is an important consideration when, for example, biological samples are being separated because fluctuating and high g-level values have the potential to damage these delicate components. This new, improved method of calculation allows for a more reliable comparison between different coil planet centrifuges and other CCC and partitioning techniques. Other factors such as the type of mixing (indicated by the critical β-values) and which phase is at the head of the column may need to be taken in into account for the optimum comparison of machines.

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