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The effect of fibre flocculation on fluidized bed expansion behaviour

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ABSTRACT

To meet tighter environmental regulations, further efforts by paper mills will be required to reduce fresh water consumption and rejects loads by moving towards closed-cycle papermaking. However, an excessive build-up of dissolved and colloidal substances in process waters will occur with major impacts on paper machine runnability and paper quality. Adsorption of specific contaminants on modified solid sorbents in a fluidized bed reactor prior to recycling is proposed. Previous results with simulated and paper machine whitewaters showed that the bed expansion follows Richardson and Zaki predictions but corrections are required to take into account the pulp suspension properties. This study shows that fibre flocculation contributes significantly to the lifting effect of beads. However, bead's properties also interfere with the flocculation process. Both phenomena are dependent on pulp fibre length, fibre coarseness, and flow rate but also on bead density and size.

1. Introduction

The papermaking industry is well known to use very large amounts of water and to produce significant volumes of wastewaters. As water resources become further stressed through increasing demands from the society, the pressure to recycle and reuse water will increase. The industry has long made important moves to reduce fresh water consumption by recycling process waters. However, further efforts will be required within 10 years to meet the strategic environmental objectives examined by the Canadian government towards maintaining a healthy environment and ecosystems. Partial closed-cycle papermaking operations are already applied in most mills. However, moving towards totally closed-cycle operations is very challenging due to major papermaking problems occurring as more process water is recycled. One of the main problems is the excessive accumulation of contaminants in process waters leading to paper machine runnability and paper quality issues [1–3]. Water recycling also leads to an increase in temperature and a reduction in dissolved oxygen, which promote corrosion and microbial activity.

To avoid the excessive accumulation of contaminants, and specifically the dissolved and colloidal substances (DCS) in process waters under highly closed systems, we propose to develop an effective methodology to remove them by their selective adsorption on modified solid sorbents (beads). Several separation technologies are available but the process must be able to handle whitewaters containing valuable cellulose particles (fibres and fines) that must be recovered in the papermaking process. The fluidization process should provide efficient adsorption of contaminants on solid sorbents while enabling the recovery of fibres and fines. This technology has successfully been used in many applications to remove heavy metal ions [4,5], humic acid [6], and proteins [7]. However, to our knowledge, very few studies have been carried out with process effluents containing wood fibres [8].

Richardson and Zaki [9] have established the general relationship describing the expansion of a bed of uniform particles with fluid velocity (Eq. (1)). The expansion coefficient (n) can be determined using numerous correlations [9–11]; the most recent being by Khan and Richardson [12]. The terminal velocity (V_T) can also be determined by a second correlation from Khan and Richardson [13] or with more classical equations from Stokes, Newton, or Van Allen.

$$\frac{V_i}{V_T} = \varepsilon^n \tag{1}$$

Eq. (1) is then used to calculate the void fraction or bed height at any fluid velocity. However, these equations are valid for pure liquid and for perfectly spherical particles. In this particular case, corrections must be applied due to the presence of fibres and fines that are expected to affect the bed expansion during fluidization. From various fluidization studies on bed expansion for beds made of binary particle sizes [14–18], we expect some interactions between fibres and the beads mainly related to the density, the size and the shape of the particles. Unfortunately, the conclusions of binary particles bed are not appropriate in our case, as most studies [14–18] are based on the heavier particles being the smallest in diameter while the lighter particles being the largest size. In our case, the bed

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Nomenclature

C_m	mass consistency (%)
L	fibre length (m)
L_w	weighted average fibre length (m)
n	expansion coefficient (dimensionless)
N	crowding factor (dimensionless)
V_i	superficial liquid velocity (m/s)
V_T	terminal velocity of the particles (m/s)
ε	void fraction (dimensionless)
ω	fibre coarseness (kg/m)

composition is the opposite in term of density and size, the heavier particles being the beads and the lighter particle, the fibres.

To better understand the bed expansion behaviour with such process waters, it is essential to include fibre and pulp suspension properties, and especially the well known effect of pulp flocculation. Fibre flocculation is a crucial characteristic in this study as in many papermaking processes involving pulp suspensions. Mason [19] showed that collisions and subsequent entanglement of fibres by shear motion of the suspending liquid are responsible for the flocculation of pulp suspensions. Moreover, Mason [20] defined the concept of dynamic equilibrium as a state in which fibre flocs continually form and disperse and where the average flocs size is determined by the level of shear strain. Higher shear strain gives in turn, smaller flocs diameter [20]. To better characterize the fibre flocculation phenomenon, Kerekes and Schell [21] have defined a crowding factor (N) which represents the number of fibres in a spherical volume of diameter equal to the length of a fibre (Eq. (2)).

$$N = \frac{5C_m L^2}{\omega} \tag{2}$$

They clearly showed a direct correlation between the crowding factor and the number of contact per fibre. Assuming that a floc is an aggregate of a minimum of 3 fibres, the corresponding crowding factor value is 60. Soszynski [22] used the crowding factor to implement flocculation regimes. In dilute regime ($N < 1$), fibres are free to move relative to each other but they occasionally collide and may remain temporarily together. In the semi-concentrated regime ($1 < N < 60$), more collisions occur between fibres with formation of transient flocs. For the concentrated regime ($N > 60$), coherent flocs are present and higher shear strength his required to break them. The fibre length is also required to calculate the crowding factor as defined in Kerekes and Schell [21]. Since a pulp's fibre length is not uniform but is rather a statistical distribution of various fibre lengths, Huber et al. [23] established a correction for the crowding factor to include such distribution phenomena.

In another report [24], bed expansion with pulp suspension has shown some significant deviation from Richardson and Zaki [9]. The impact of fibres concentration (pulp consistency) was clearly affecting the terminal velocity of the beads and the expansion coefficient, but the flocculation behaviour was not studied. Fibre properties and especially fibre flocculation play a significant role on flow dynamics, bed expansion behaviour, and consequently on the fluidized bed reactor design. The objective of this study is to determine the effect of pulp flocculation on the bed expansion behaviour during fluidization.

2. Materials and methods

2.1. Materials

Soda-lime glass (Fisher Scientific), acrylics, and stainless steel beads (Salem Ball) of 3 and 4 mm in diameter were used for fluidization trials. Beads properties are presented in Table 1.

Pulp from different pulping processes was selected to obtain different fibre lengths and fine contents. Stone groundwood (SGW), thermomechanical (TMP), and Kraft pulps were supplied by an Eastern Canadian paper mill. A typical newsprint paper machine whitewater (WW) sampled at the same paper mill was also tested for comparison purposes. Pulp slurries were prepared as described in TAPPI (Technical Association of the Pulp and Paper Industry) standard method T-262 and the concentration of fines and fibres were determined using TAPPI standard method T-240. Concentration of fines and fibres (consistency) is defined as the weight percentage of oven-dry fibre over the total weight of the pulp suspension. Fibre length and coarseness were determined using a Fibre Quality Analyzer (FQA) according to TAPPI standard method T-271. Pulp slurries were allowed to stabilize at room temperature (25 °C) prior to fluidization experiments. Pulps and whitewater properties are presented in Table 2.

2.2. Methods

A schematic diagram of the experimental setup is shown in Fig. 1.

The fluidization column (2.2 m in height, 6.16 cm inner diameter) was filled with 1.5 kg of the appropriate beads and the initial height was recorded for future reference. The liquid fed at the bottom of the column was distributed by a cone of 46.6° inside angle and 7.62 cm in height. The control experiments were carried

Table 1
Beads characteristics.

	Diameter (mm)	Density (kg/m^3)	Archimedes number (25 °C water)
3 mm acrylic	3.00 ± 0.01	1196 ± 4.7	6.52×10^4
4 mm acrylic	3.96 ± 0.01		1.37×10^5
3 mm soda-lime glass	2.93 ± 0.04	2616 ± 30.1	5.05×10^5
4 mm soda-lime glass	3.96 ± 0.03		1.36×10^6
3 mm stainless steel	2.99 ± 0.01	8044 ± 4.1	2.30×10^6
4 mm stainless steel	3.99 ± 0.01		5.37×10^6

Table 2
Pulps properties.

	Stone groundwood (SGW)	Thermomechanical pulp (TMP)	Kraft	Newsprint whitewater
Arithmetic average fibre length (mm)	0.28	0.66	1.21	0.16
Length-weighted fibre length (mm)	0.63	1.56	2.22	0.33
Fines content (%)	62.1	33.8	25.4	84.5
Coarseness (mg/100 m)	18.9	22.8	15.3	22.8

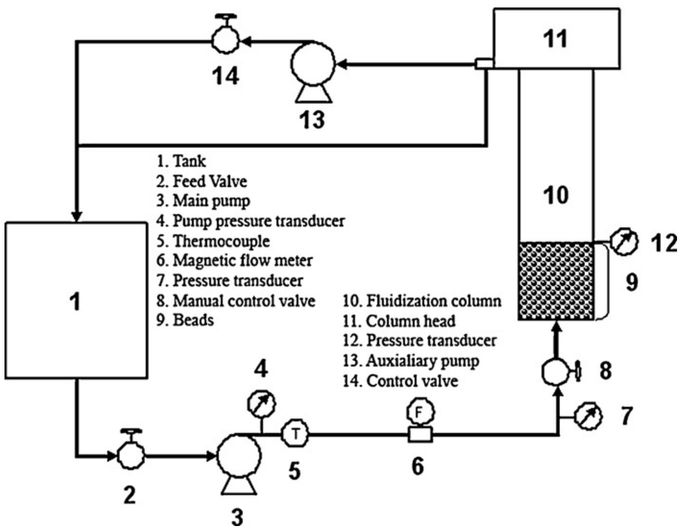

Fig. 1. Schematic diagram of the experimental fluidized bed reactor.

with tap water adjusted at the desired temperature (25 °C) and for pulp slurries with consistencies up to 0.2%. Expansion curves were obtained by adjusting the flow rate to a predetermined value ranging from 0 to 70 L/min, and the resulting height of the bed was determined using a graduated tape positioned on the outside surface of the fluidization column. Three trials were carried out for each experimental condition. Further details on the experimental setup can be found in a previous report [8].

3. Results and discussion

3.1. Fluidization with water

Fig. 2 presents fluidization trials with water for acrylic, glass, and stainless steel beads. As for all figures in this report, the solid lines in Fig. 2 are the result of a second order polynomial fit. As described by Richardson and Zaki [9], results indicate that bed expansion is strongly dependent on bead density. As density rise, the flow rate required to achieve a given bed expansion increases. The relative bed expansion of acrylic beads varies almost linearly with flow rate while it exhibits an exponential trend for glass and stainless steel beads.

Fig. 2 also presents the effect of bead diameter. The flow rate required to expand the bed is higher for 4 mm diameter than for 3 mm diameter beads. In fact, for a given bead density and flow rate,

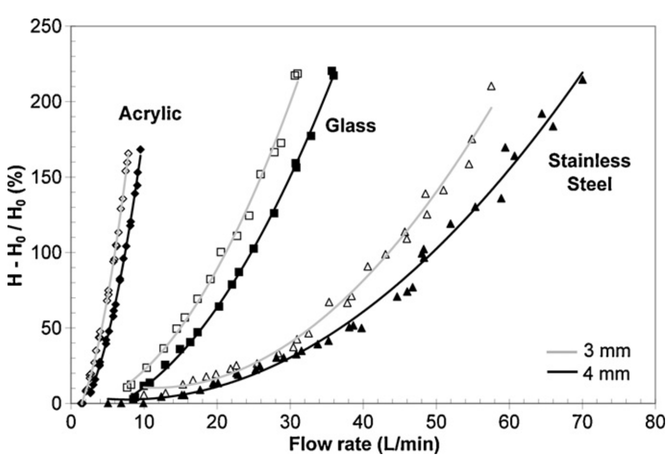

Fig. 2. Bed expansions with water for acrylic, glass and stainless steel beads at 25 °C.

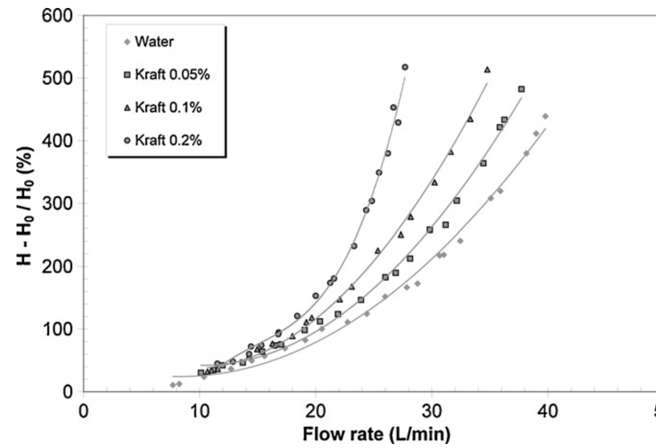

Fig. 3. Bed expansions with Kraft pulp slurries for 3 mm soda-lime glass beads at 25 °C.

a 35% relative bed height difference between both beads is observed since larger beads are heavier, thus requiring a greater force to lift them up in the liquid phase. Results from water fluidization experiment are validating our experimental setup from an operational point of view and from the known fluidization behaviour. The fluidization water curve will establish the baseline for future interpretation.

3.2. Fluidization with pulp suspensions

Fig. 3 presents the effect of flow rate on bed expansion for Kraft pulp suspensions at different consistencies (wt%) for 3 mm soda-lime glass beads. Results indicate the presence of two different flow regimes ranging around 15 L/min. At low flow rates (<15 L/min), Kraft pulp suspensions behaved much like water, while at higher flow rates (>15 L/min), the bed expansion increased with pulp consistency. This could be mostly attributed to several parameters, namely fibre collisions with beads, fibre properties (length, coarseness), pulp properties (consistency, fibre length distribution), fibre flocculation and floc strength, and hydrodynamic forces resulting from flow conditions (turbulence). However, fibre flocculation and floc strength are probably the most important factors affecting bed expansion.

Kraft pulps are mainly composed of long fibres as shown in Table 2. It is well known that collisions and subsequent mechanical entanglement of fibres caused by the motion of the suspending liquid are the primary factors controlling the flocculation process [25]. Flocculation is also very dependent on fibre concentration. Kerekes and Schell [21] defined a crowding number to characterize a pulp suspension. This number is accounting for fibre morphology (length, coarseness) as well as fibre concentration and is related to pulp flocculation potential. The calculated crowding factors for 0.05%, 0.1% and 0.2% slurry consistency studied are respectively 0.5, 1.1 and 2.1 for SGW, 2.7, 5.3 and 10.7 for TMP and 8.1, 16.2 and 32.4 for Kraft pulps. The newsprint paper machine whitewater was at a consistency of 0.31% yielding a crowding factor of 0.8.

On the other hand, floc strength could also play a significant role on bed expansion. Flocs are coherent three-dimensional networks of fibres exhibiting considerable strength to shearing [26]. Thalen and Wahren [27] have shown that the strength of a fibre network is closely related to the consistency, the Young elastic modulus, and the length to diameter ratio of the fibres. Depending on turbulence conditions, transient and coherent flocs can be found in pulp suspensions [25]. Therefore, these parameters must be taken into account since the pulp is flowing into a vertical column containing a bed of beads of various characteristics.

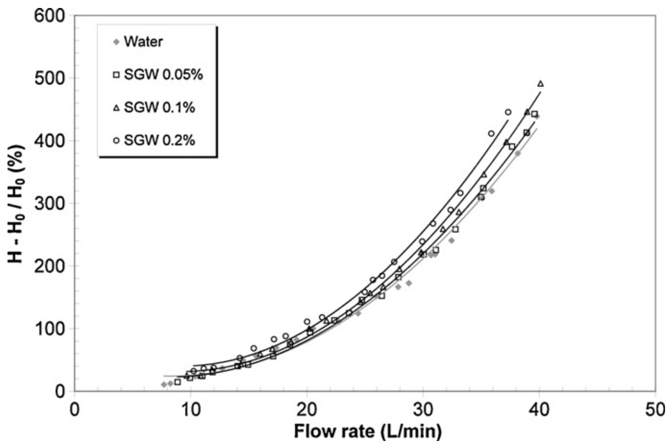

Fig. 4. Bed expansions with SGW pulp slurries for 3 mm soda-lime glass beads at 25 °C.

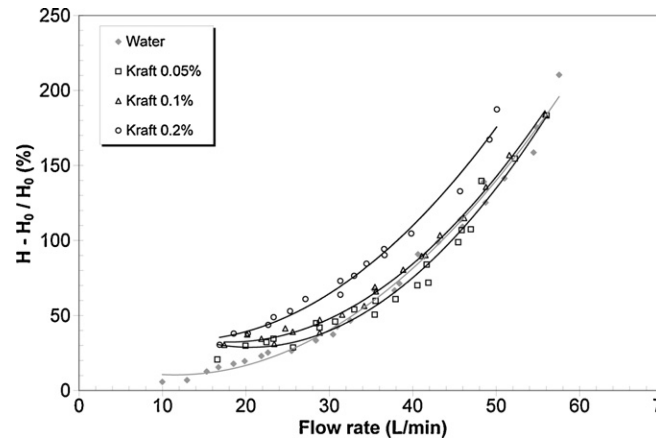

Fig. 5. Bed expansions with Kraft pulp slurries for 3 mm stainless steel beads at 25 °C.

A careful analysis was carried out to explain bed expansion behaviour for pulp suspension trials at both established flow regimes. At low flow rates (<15 L/min), the bed is not fully expanded. Under such conditions, beads are more closely packed (low void fraction in the bed), thus creating a larger restriction to the flow of the pulp suspension (higher pressure drop). Although the lower flow rate used, flocs formed below the bed are probably broken down due to collision with the beads. It is likely that no coherent flocs are formed under these operating conditions. Individual fibres or very small and strong transient flocs can thus cross the bed without any significant contribution to lift beads. At higher flow rates, the bed is expanded in a similar manner than with water alone with much more space between beads (high void fraction). The pressure drop is also lower than at low flow rates. It has also been noticed that the expanded bed is stretched at higher flow rates resulting in a void fraction gradient from bottom to top. This gradient is probably attributed to a lifting effect of the beads by larger coherent flocs formed within the expanded bed. Moreover, since the bed is expanding in the column, it leaves time for fibres to reflocculate as they are travelling towards to top of the column [28]. Since the turbulence level is decaying from the bottom of the column (where the suspension is entering) to the top, it is likely that flocculation of long Kraft fibres into large and strong flocs is occurring during fluidization [20]. This phenomenon is probably contributing to lift the beads during fluidization, much like a screen mesh. Therefore, the increase in bed expansion observed in Fig. 3 for a given flow rate (especially at flow rates higher than 15 L/min) is most likely attributed to Kraft pulp flocculation occurring in the fluidization column during trials.

Similar experiments were carried out with shorter fibres. Fig. 4 shows the effect of flow rate on bed expansion for SGW pulp suspensions at various consistencies. Low variations are observed for trials at consistencies studied. In fact, 0.05% consistency suspensions behaves very much like water, while 0.1% and 0.2% slurry consistencies show only small deviations from the water curve. The expansion of the bed is very low compared to trials with Kraft pulp slurries. This could be attributed to the lower flocculation potential of short fibres as discussed previously. As fibre length decreases, the crowding factor or the flocculation potential also decreases [29,30].

Although the flocculation potential is smaller for SGW than Kraft fibres, for the same slurry consistency and fibre coarseness, SGW pulps contains more fibres than Kraft pulp by unit volume. Thus, the beads–fibres collision potential, if any, must be higher for SGW pulps. The relative density of a fibre and a bead is quite important in collision phenomenon. The fact that Fig. 4 shows a negligible contribution of fibres–beads collision on the final bed height could be attributed to the density ratio of the soda-lime glass bead (2616 kg/m^3) and a black spruce fibre (about 1200 kg/m^3). It is thus likely, that the kinetic energy of shorter SGW fibres is too low to contribute for the lifting action of the bead. Therefore, short fibres are probably following the flow field around the bead and sliding away.

In order to assess the effect of a heavier bead, experiments were carried out with 3 mm stainless steel beads. Fig. 5 shows the bed expansion for Kraft pulp suspensions at various consistencies. Results indicate that flocculation had almost no effect on bed expansion except for trials with Kraft pulp at 0.2% consistency. Therefore, the lifting contribution of flocs is only significant for trials at 0.2% consistency, indicating that fibre networks are just strong enough to support heavier beads. This is thus in agreement with findings of Andersson et al. [31] for floc strength, which is proportional to the number of contact points between fibres and to the square of the volumetric concentration or consistency. However, some discrepancies were observed for data at low flow rates for all trials carried out in this series of experiments. The offset found can be attributed to a partial bed plugging by pulp fibres, resulting in an overall slight bed expansion.

Fig. 6 shows the effect of flow rate on bed expansion for SGW pulp suspensions. The trend observed at any pulp consistencies is very similar to trials with water alone. This is a clear indication that flocs are too weak to contribute significantly to the lifting effect as it was observed for the same pulp suspensions with lighter glass beads (Fig. 4). If any, the effect of fibres–beads collision is even

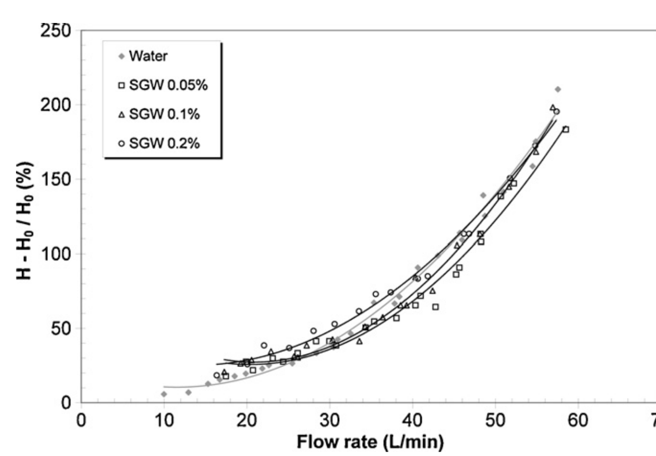

Fig. 6. Bed expansions with SGW pulp slurries for 3 mm stainless steel beads at 25 °C.

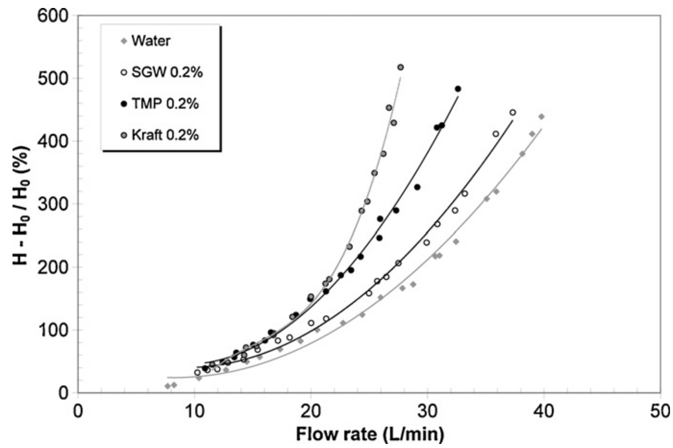

Fig. 7. Bed expansions with various pulp slurries at 0.2% consistency for 3 mm soda-lime glass beads at 25 °C.

smaller than for soda-lime glass (Fig. 4) and cannot account for these variations.

Fluidization trials were also carried out with a lighter bead (acrylic). Unfortunately, data were very difficult to reproduce and will not be shown in this study.

It should be noted, that Figs. 3–6 are showing the expansion curves for 3 mm beads diameter but the conclusions are similar for the 4 mm beads (data not shown). Surprisingly, data comparison for any pulp–bead combinations shows a 35% difference in bed height between 3 and 4 mm beads, within the experimental error. This result was also observed for trials with water alone, as reported previously. Therefore, it is expected that 4 mm beads will behave similarly to 3 mm beads.

To summarize, Fig. 7 compares the effect of each pulp suspensions at 0.2% consistency on bed expansion for 3 mm glass beads. Results clearly demonstrate our assumption of the effect of pulp flocculation on bed expansion for low and high flow rates. Therefore, pulp characteristics do have a strong effect on bed expansion. The identification of flocculation as a key component in the deviation of fluidization curve from the ideal Richardson and Zaki [9] was confirmed in a previous study [8]. The authors have related successfully the terminal velocity of the beads to dimensionless number such as Archimedes and the crowding factor defined earlier in this report. The expansion coefficient was also found to be related to the crowding factor and Archimedes but also to the beads density.

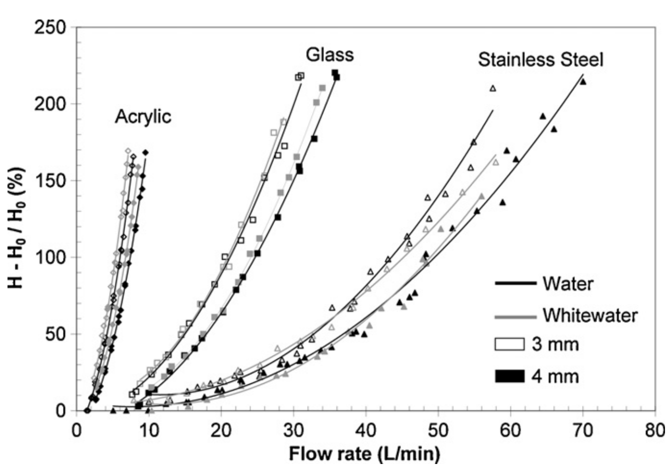

Fig. 8. Bed expansions for tap water and newsprint whitewater at 25 °C.

3.3. Fluidization with newsprint paper machine whitewater

Finally, trials with a typical newsprint paper machine whitewater were carried out for comparison purposes with simulated pulp suspensions. According to fibre length and crowding factor data, newsprint whitewater is very similar to SGW pulp slurry. Since newsprint whitewater has a low flocculation potential, a low lifting effect of beads during fluidization should occur.

Fig. 8 presents the expansion curves for 3 and 4 mm acrylic, glass, stainless steel beads for water and newsprint whitewater at 0.31% consistency. As expected, very small deviations from the water curves are observed for any bead combinations (compare grey vs black lines). Taking into account the low standard deviation determined in [8], the difference between the curves is within the experimental error.

4. Conclusions

The purpose of this work was to determine the effect of fibre flocculation on fluidized bed expansion behaviour. The following are the major findings of this study:

1. At flow rate higher than 15 L/min (0.084 m/s), the flocculation of the pulp during fluidization was found to exert a very significant effect on bed expansion. This effect was attributed to a lifting phenomenon of the beads by strong coherent fibre flocs formed within the bed.
2. Pulp characteristics, such as fibre length, fibre coarseness, and consistency have a strong effect on bed expansion. However, network strength is a dominating factor in bed expansion behaviour.
3. As expected, beads characteristics (density and diameter) were found to have a significant impact on the floc strength required to exert a flocculation effect.
4. Newsprint paper machine whitewaters behave much like short fibre pulp suspensions (SGW) as their flocculation potential is low.

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