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Evaluation of the effect of feed canal height on membrane clarification efficiency of pomegranate juice using computational fluid dynamics (CFD)

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ABSTRACT

Pomegranate juice in its turbid appearance is difficult to preserve; hence, it should be clarified. Microfiltration is a pressure-driven process which can be used to clarify pomegranate juice. Computational fluid dynamics was used to simulate the effect of feed canal height on efficiency of the membrane clarification of pomegranate juice. Geometry of membrane unit was plotted in Gambit software and meshed with quad-mapped meshes, and the problem was solved using FLUENT software. Boundary conditions were identified in both Gambit and FLUENT. Two-dimensional double precisions procedure was selected in FLUENT software. Selected solver was segregated one at steady state. Membrane was defined with three parameters in FLUENT including face permeability, membrane thickness, and pressure jump coefficient. Results of simulation showed that permeate volume was directly dependent on feed canal height. Experimental results were in agreement with the results which were obtained from simulation.

Keywords: Clarification; CFD; Membrane; Pomegranate; Simulation

1. Introduction

Pomegranate juice has a turbid appearance which makes difficulty in its concentration process due to produce off-flavor; hence, it must be clarified to remove large particles [1]. Microfiltration (MF) is a pressure-driven process which can be used to clarify pomegranate juice [2]. There are several parameters affected on the efficiency of membrane clarification such as transmembrane pressure, feed-flow rate, and feed temperature [3,4].

Computational fluid dynamics (CFD) is a potential method which can be used to predict the effect of process parameters on membrane process. Mirsaeedghazi et al. [5] used CFD to model the microfiltration process in clarification of pomegranate juice and found optimum values of process parameters. Pak et al. [6] modeled microfiltration of water with CFD to evaluate the effect of geometrical dimension, membrane surface area, Reynolds number, and membrane fouling on the permeate flux. Wiley and Fletcher [7] developed CFD model to evaluate the pressure-driven membrane processing in which there is selective passage of substances through the membrane. They investigated the

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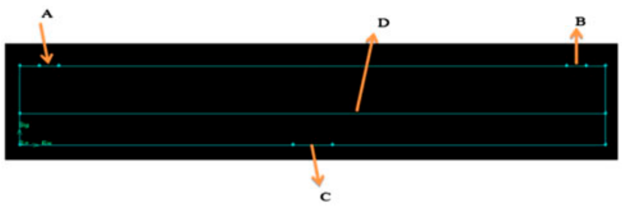

Fig. 1. Geometry of the membrane module which was used to clarify pomegranate juice (A–D are feed entrance, retentate exit, permeate exit, and membrane, respectively).

effect of concentration polarization and velocity profile on the permeate flux. Rahimi et al. [8] simulate the microfiltration of water with CFD. They compared CFD and experimental methods to evaluate the effect of transmembrane pressure and fluid mass flow rate on permeate flux and resulted that there is good correlation between them.

There is no study about the effect of feed canal height on the efficiency of membrane clarification of pomegranate juice. In current work, membrane clarification of pomegranate juice was simulated with CFD to evaluate the effect of feed canal height (as representative of feed volume) on permeate flux.

2. Materials and methods

2.1. Development of the geometry of system

The flat sheet membrane module with 150-mm length and 85-mm width was used (Fig. 1). Three

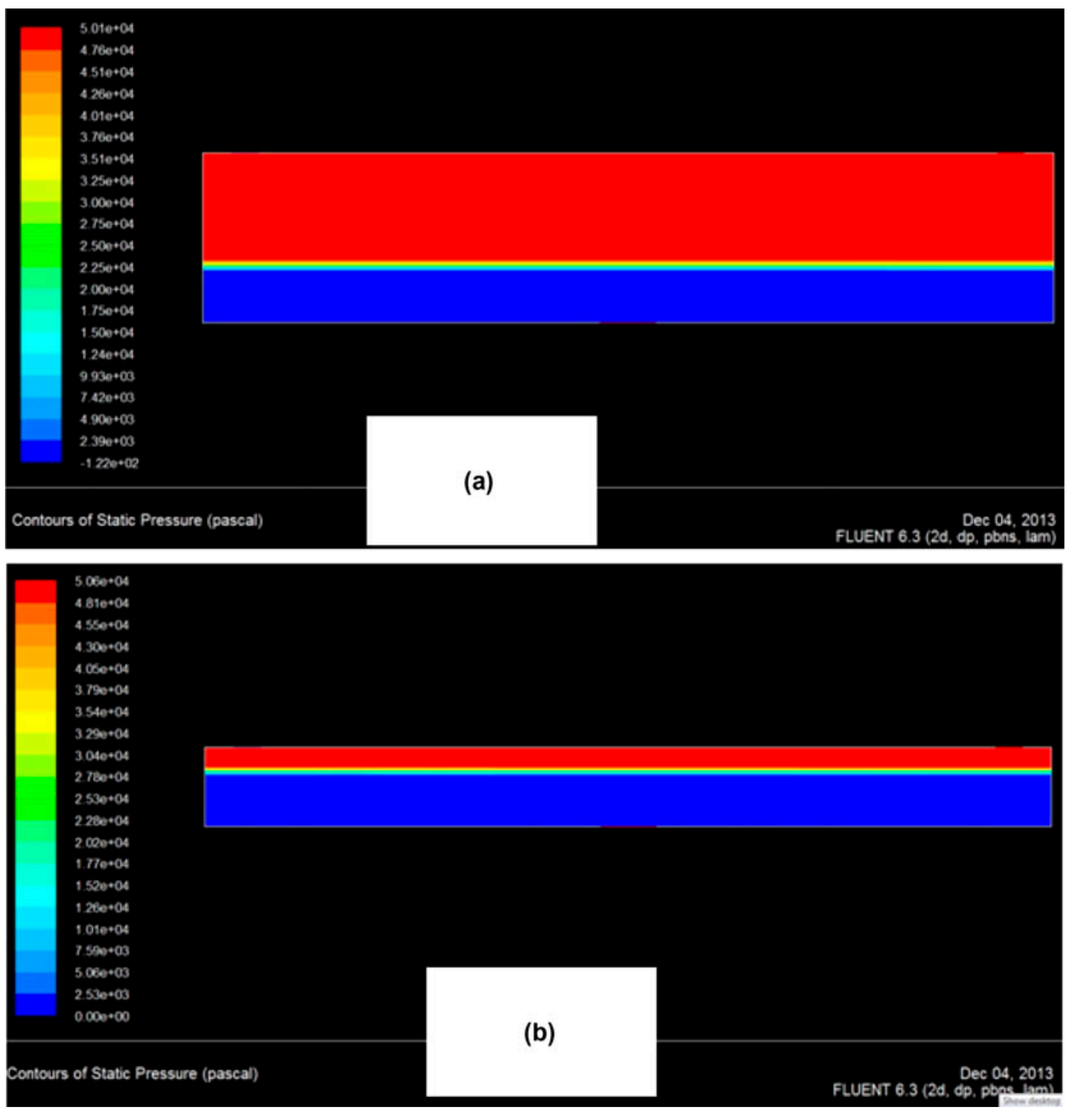

Fig. 2. Counter of pressure in flat sheet membrane module (a) feed canal height = 2 cm and (b) feed canal height = 0.4 cm.

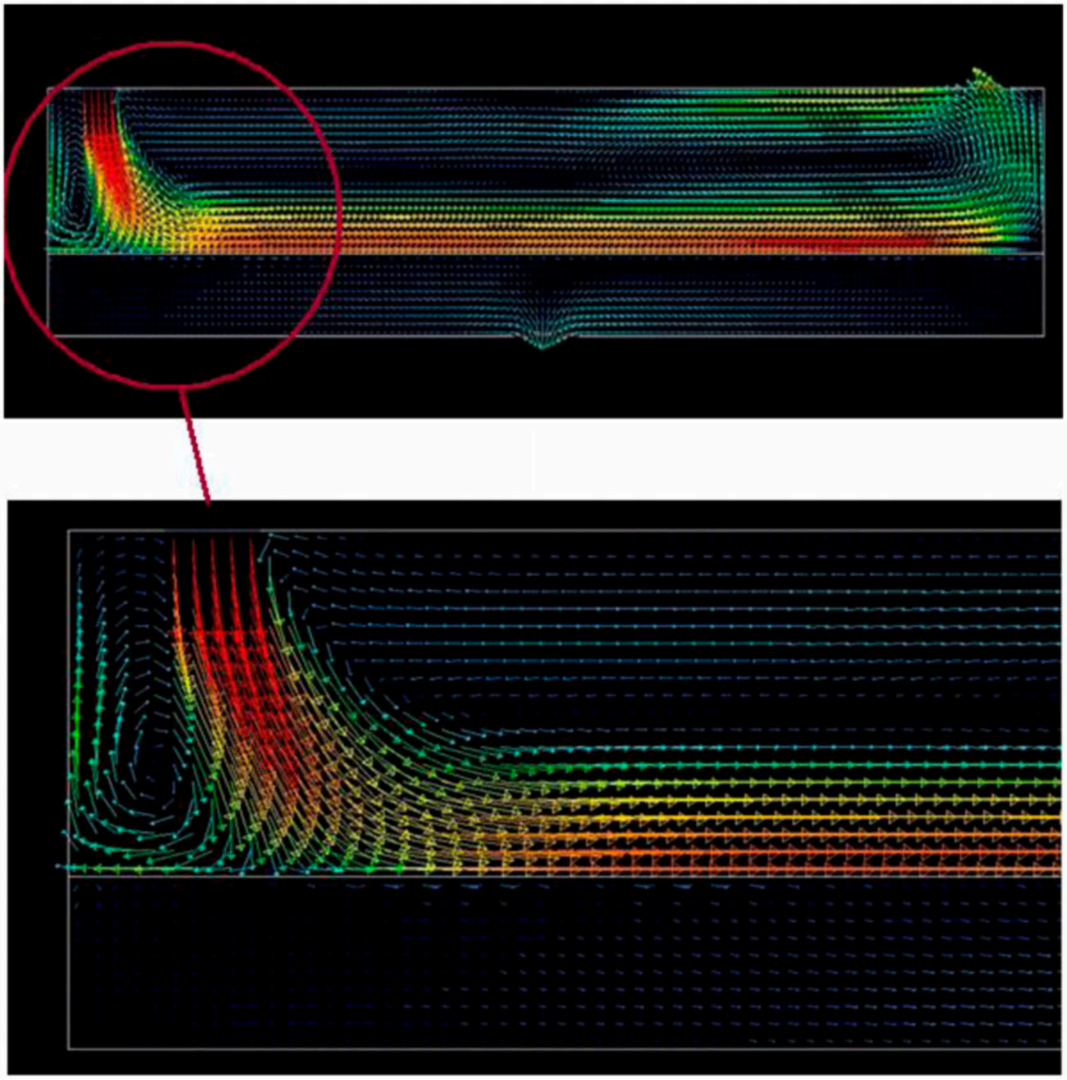

Fig. 3. Vector of flow in flat sheet membrane module (feed canal height = 2 cm).

different feed canal heights (0.4, 1.5, and 2 cm) were selected to evaluate its effect on the efficiency of clarification process. Gambit (version 2.4.6) was used to plot the geometry of membrane module in cross-flow pattern.

2.2. Meshing

A meshing with double-sided ratio 1.1 and 0.05 spacing interval size was chosen for vertical walls. Also, the membrane and other horizontal walls including inlet, outlet, and the permeate exit were meshed with interval size of 0.2. The meshes were finer near the inlet channel, outlet channel, and around the membrane surface due to high changes in flow dynamic behavior near these walls. All meshes had quad-mapped type. Final mesh has 18,361 nods and 18,000 elements.

2.3. Boundary conditions in Gambit

The membrane was assumed as a porous jump in Gambit, and other boundary conditions were as follows:

- Feed entrance as velocity inlet.
- Retentate exit as pressure outlet.
- Permeate exit as pressure outlet.
- Other surfaces as wall.

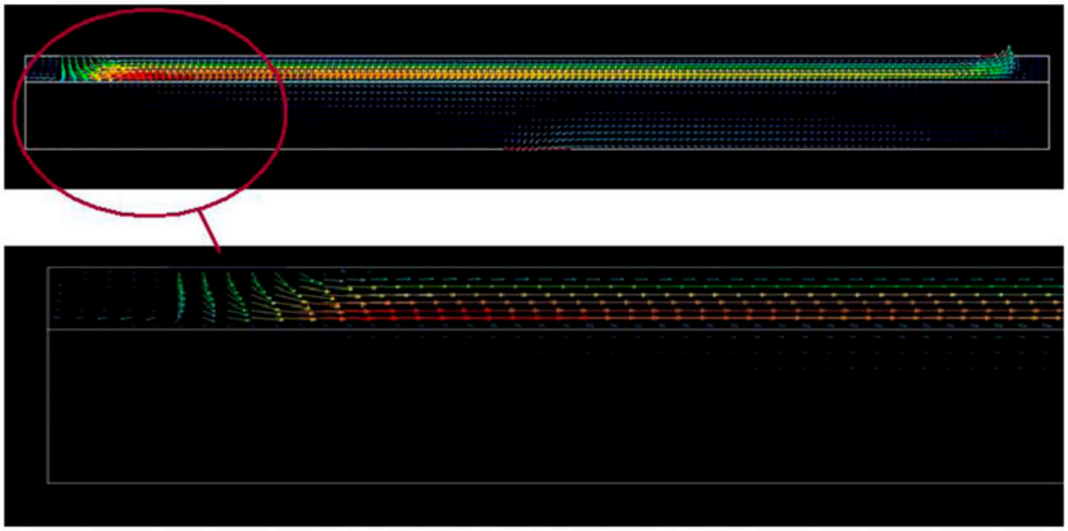

Fig. 4. Vector of flow in flat sheet membrane module (feed canal height = 0.4 cm).

2.4. Solution method

After defining boundary conditions in Gambit, final structure was exported to FLUENT software version 6.3.26 to solve the problem. Two-dimensional double precisions procedure was selected in FLUENT software. Selected solver was segregated one at the steady state, and material density and viscosity were adjusted at 1.063 kg/m^3 and 1.7 × 10^{-3} kg/ms, respectively. The pressures of permeate and retentate were considered as 0 and 0.5 bar, respectively. Feed velocity was adjusted at constant level with changing its flow rate in different channel heights to remove the effect of shear rate on reduction of membrane fouling, and consequently on permeate flux.

Membrane was defined with three parameters in FLUENT software including face permeability, membrane thickness, and pressure jump coefficient. The face permeability was calculated according to the following equation:

$$\alpha = \frac{D_p^2 \epsilon^2}{150(1-\epsilon)^2} \tag{1}$$

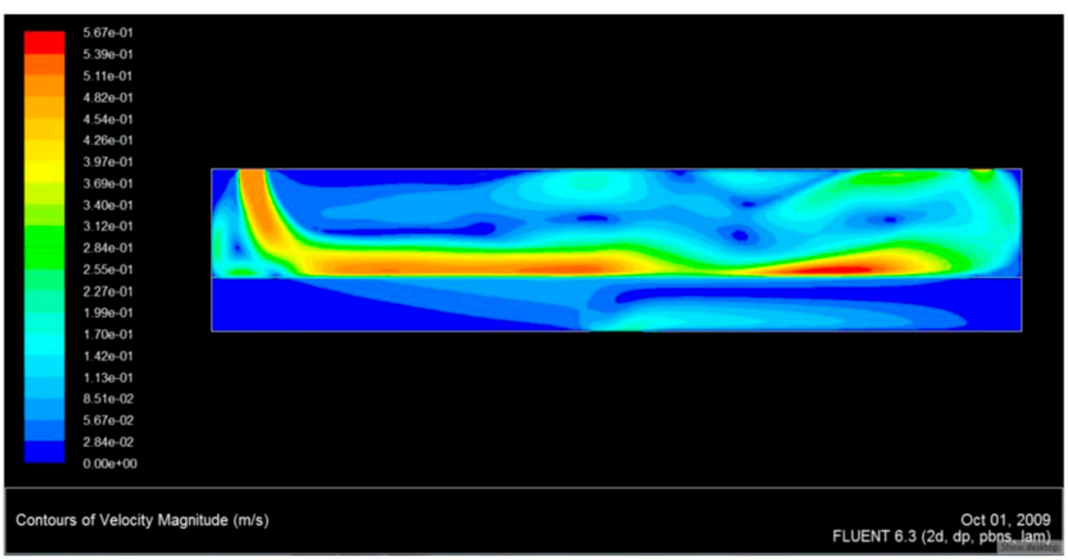

Fig. 5. Vector of velocity in flat sheet membrane module (feed canal height = 2 cm).

in which D_p and ε were average particle diameter of pomegranate juice and the membrane void, respectively.

The pressure jump was calculated with the equation:

$$C_2 = \frac{3.5(1 - \epsilon)}{D_p \epsilon^2} \tag{2}$$

Verifying the developed model.

2.5. Juice extraction

Pomegranate (variety Malase Saveh) was prepared from local market (Saveh, Iran). Maturated fruits were selected and washed, and their leathery skins were removed. Pomegranate juice was manually extracted with pressing the fruit sacs and large particles such as skin pieces were removed using mesh filter (pore size of 1 mm). Extracted juice was filled in PET bottle.

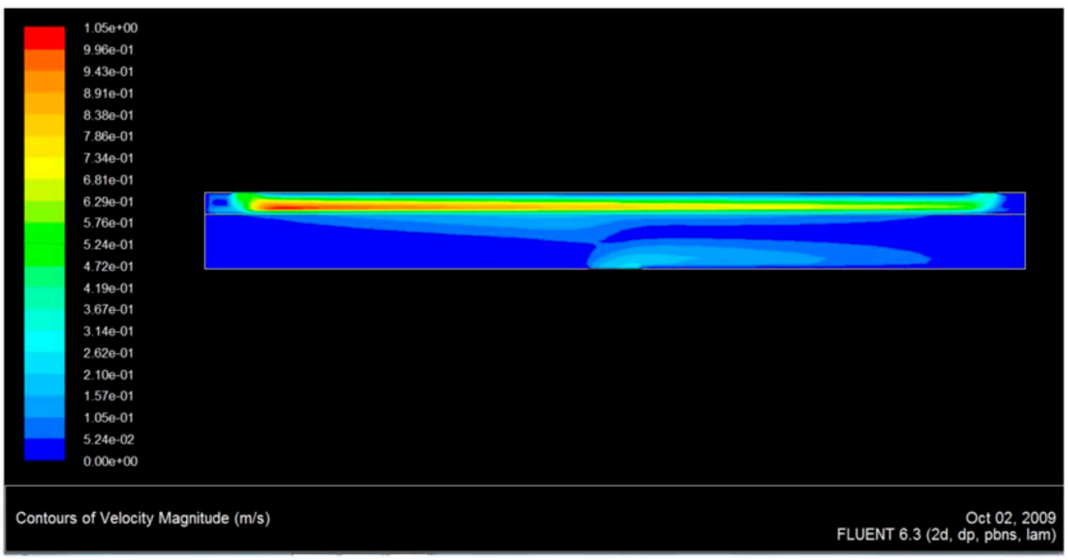

Fig. 6. Vector of velocity in flat sheet membrane module (feed canal height = 0.4 cm).

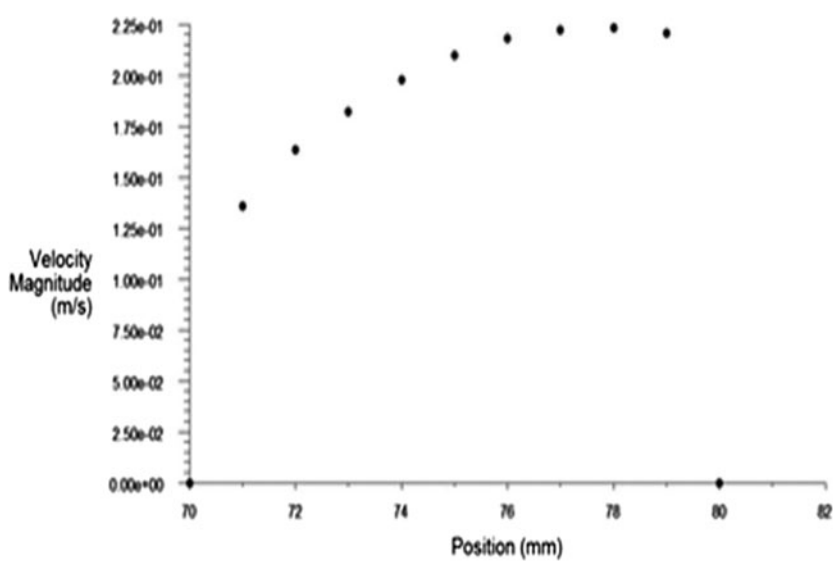

Fig. 7. Vector of velocity at outlet of permeate in flat sheet module (feed canal height = 0.4 cm).

2.6. Membrane unit

Cross-flow microfiltration unit in bath mode and laboratory scale was selected to clarify pomegranate juice. The membrane type was mixed cellulose ester (Millipore, USA) with pore size of 0.22 µm and active surface area of 0.013 m^2. Membrane porosity was 75%, and its thickness was 150 µm. Feed canal has three different heights (0.4, 1.5, and 2 cm) to compare the effect of feed canal height on volume of clarified pomegranate juice. Feed was pumped from feed tank to flat sheet module, and the retentate was recycled. Permeate was collected in permeate tank which was on digital balance to measure the weight of clarified juice. A transmitter (WIKA, type ECO-1, Klingenberg, Germany) coupled with an inverter (LS, model sv015ic5-1f, Korea) along with a flow meter was used to adjust constant transmembrane pressure (0.5 bar) at different feed-flow rates in all canal heights. Also, feed temperature was 25˚C in all experiments.

2.7. Calculation of permeate flux

Permeate flux (J, kg/m^2 s) was calculated according to Eq. (3), as follows:

$$J = \frac{1}{A}\frac{\mathrm{d}w}{\mathrm{d}t} \tag{3}$$

in which A, w, and t are membrane active area (m^2), permeate weight (kg), and time (s), respectively.

3. Results and discussion

Microfiltration is a pressure-driven process [2]; hence, permeate flux can change with variation in transmembrane pressure. Counter of transmembrane pressure (Fig. 2) showed that there is a similar transmembrane value in both feed canal heights (0.4 and 2 cm). So, it is guaranteed that any change in permeate flux is away from the effect of transmembrane pressure. Consideration of the counter of feed flow over the membrane surface showed that both canals (with heights of 0.4 and 2 cm) are filled with feed and there is no space in feed canals (Figs. 3 and 4). On the other hand, according to Hojjatpanah et al. [4], membrane fouling and permeate flux were dependent on feed velocity; so, feed-flow rates were adjusted to keep feed velocity constant in different feed canal heights.

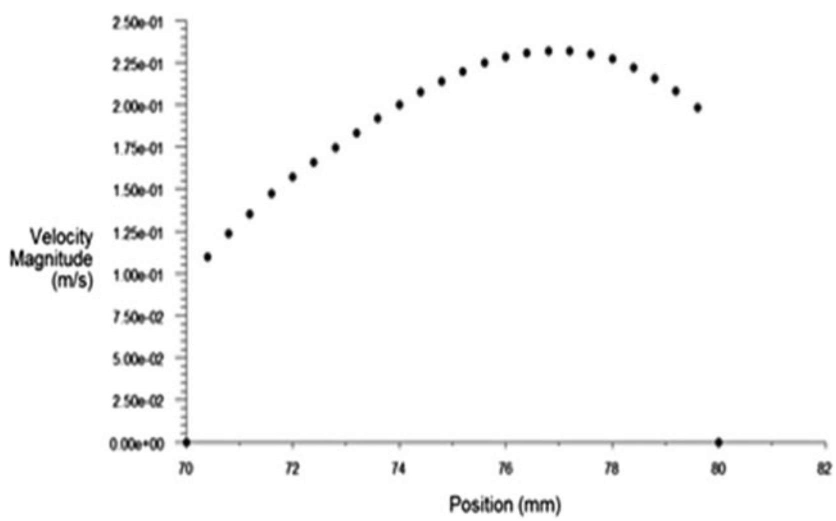

Fig. 8. Vector of velocity at outlet of permeate in flat sheet module (feed canal height = 2 cm).

Table 1.
Permeate volume in different feed canal height predicted by CFD

Feed canal height (cm)	Volumetric flow rate of permeate (m^3/s)
0.4	0.001284
1	0.001320
2	0.001322

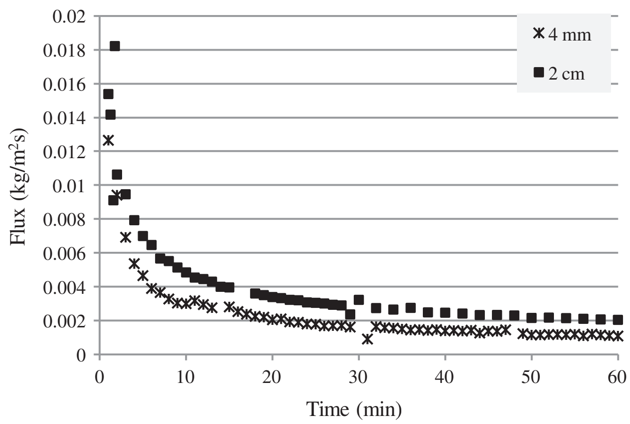

Fig. 9. Experimental data of the effect of feed canal height on permeate flux during membrane clarification of pomegranate juice.

The vector of velocity in flat sheet module with feed canal height of 2 cm showed that in the input section of feed canal, the velocity was much more than its value in the output section (Fig. 5). It is due to separation of permeate from the feed over the membrane surface and consequently decrease the feed volume. On the other hand, feed velocity increased at the surface of membrane due to existence of transmembrane pressure on the membrane surface and the barrier effect of membrane against feed-flow direction. Also, vortex flows were seen in the feed canal. The velocity value below the membrane (in the permeate canal) was much lower than its value in feed canal due to selective effect of membrane on pomegranate juice where a small fraction of juice was allowed to pass through the membrane. There is similar velocity value pattern in the membrane module with feed canal height of 0.4 cm (Fig. 6). It shows that the value of permeate flux does not affected by feed velocity.

Evaluation of permeate velocity in its outlet section (Figs. 7 and 8) showed that its value increased in right section of permeate canal (feed output side) due to return flow which was created in feed canal near the output section (Figs. 5 and 6). On the other hand, maximum value of permeate velocity increased with raising feed canal height. The volumetric flow rate of permeate was evaluated to study the effect of feed canal height on the efficiency of membrane clarification. Results (Table 1) showed that the volumetric flow rate of permeate increased with increasing the feed canal height which was in agreement with previous finding in (Figs. 7 and 8). Because of equal level of transmembrane pressure, feed velocity, and feed temperature, it is suggested that increasing the permeate volume after increasing the feed canal height can be attributed to more feed volume in high canal height than its value in low canal height.

In total, current simulation showed that permeate volume was directly dependent on feed canal height. So, the pomegranate juice was clarified to verify the results which were obtained with CFD. Two membrane units which were only different in their feed canal heights were selected to clarify pomegranate juice. Results showed that the permeate flux increased with increasing feed canal height (Fig. 9) which was in agreement with the results obtained from simulation.

4. Conclusion

Simulation of the membrane clarification of pomegranate juice showed that the permeate flux is dependent on the height of feed canal. So that the permeate flux increases with increasing the feed canal height. The experimental results confirm the results which were obtained from simulation. It was concluded that the efficiency of membrane clarification can be increased with increasing feed canal height.

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