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Evaluation of a tubular heat exchanger for preheating a cell suspension of Tsukamurella paurometabola

Evaluación de un intercambiador de calor tubular para el precalentamiento de una suspensión celular de Tsukamurella paurometabola

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Abstract

Today, the development and implementation of more efficient and profitable thermal processes constitute a topic with high priority in a great amount of industries and chemical plants. At the present work the experimental evaluation of a tubular heat exchanger is carried out in order to preheat a liquid cell suspension (bio-formulate) of *Tsukamurella paurometabola* bacteria strain C-924, as an alternative to substitute the current batch preheating method. Cell viability studies, as well as chemicals and electricity consumption studies, were carried out for both preheating methods considered (batch and continuous), while the results obtained were mutually compared. Batch preheating mode reduces the cell viability of the bio-formulate in 75% during the first 6 hours of preheating, while the application of the continuous preheating method using the tubular heat exchanger don't reduces the viability of the bio-formulate. The dehydrated powder obtained by the continuous preheating approach had a viability value 1.37 times higher than the powder obtained during batch preheating method. The cost involved due to electricity consumption is 1.4 times higher in batch preheating method as compared with continuous preheating process, while regarding reagents consumption it is near 3 times higher. It's concluded that the proposed tubular heat exchanger constitutes a profitable and feasible alternative to apply during the bio-formulate preheating step in substitution of the actual batch preheating procedure.

Keywords: Tubular heat exchanger, bio-formulate, cell viability, cost.

where

$t_{oper(i)}$ = Operating time of the equipment *i* (h)
P_i = Nominal power of the equipment *i* (kW)
C_{elect} = Electricity cost = 1.20 $/kWh
$C_{power(i)}$ = Cost associated with the electricity consumption by the equipment *i* ($)

Finally, the total cost involved due to electricity consumption by all the equipment used during preheating process will be

$$C_{power(T)} = \sum_{1}^{n} C_{power(i)} \tag{2}$$

where

n = Amount of equipment used during preheating process.

Chemicals: Table 2 shows the amount consumed and the unit cost of each reagent used in both preheating methods.

The cost related with the consumption of the reagent *i* during preheating process will be determined according to the following expression

$$C_{reag\,(i)} = Q_{reag\,(i)} \cdot P_{reag\,(i)} \tag{3}$$

where

$Q_{reag(i)}$ = Amount of the reagent *i* consumed [kg or L]
$P_{reag(i)}$ = Unit cost of the reagent *i* ($/kg or $/L)
$C_{reag(i)}$ = Cost associated with consumption of the reagent *i* ($)

The total cost involved due to reagent consumption will be

$$C_{reag\,(T)} = \sum_{l}^{n} C_{reag\,(i)} \tag{4}$$

where

n = Amount of reagent consumed during preheating process.

Table 2. Summary of the different reagents consumed for both preheating methods

Chemical	Amount consumed	Unit cost
Batch preheating		
Sodium hydroxide (pellets)	80 g	$ 0,054/kg
o-Phosphoric acid	30 mL	$ 0,2352/L
Water	60 L	$ 0,05/L
Continuous preheating		
Sodium hydroxide (pellets)	40 g	$ 0,054/kg
o-Phosphoric acid	15 mL	$ 0,2352/L
Water	20 L	$ 0,05/L

Geometric dimensions of the proposed tubular heat exchanger

The tubular heat exchanger proposed presents the following geometrical dimensions (Table 3).

Table 3. Geometric dimensions of the tubular heat exchanger proposed

Variable	Value	Units
Annulus		
Inner diameter	0.074	m
Outer diameter	0.076	m
Inner tube		
Inner diameter	0.0555	m
Outer diameter	0.0575	m
Other		
Length	0.35	m
Material	Stainless Steel	

Results and discussion

Results obtained for the two viability studies accomplished for the batch preheating process

Two viability studies were carried out in order to determine the influence of batch preheating time in the cell viability of the bio-formulate. The results obtained for the first experimental viability study accomplished, that is, batch preheating of the bio-formulate for 40 hours, are showed in Figure 4, while Figure 5 shows the results obtained for the second experimental cell viability study realized, that is, batch preheating of the bio-formulate for 6 hours.

where

X_V = Viable cells count at time t
X_O = Viable cells count at initial time 0

Analyzing the results obtained in Figure 4 it can be observed that in the first 6 hours of preheating a 75% reduction of bio-formulate cell viability occurs. This is because a progressive nutrient and oxygen consumption takes place throughout almost all the time the batch preheating process lasts, which causes that the

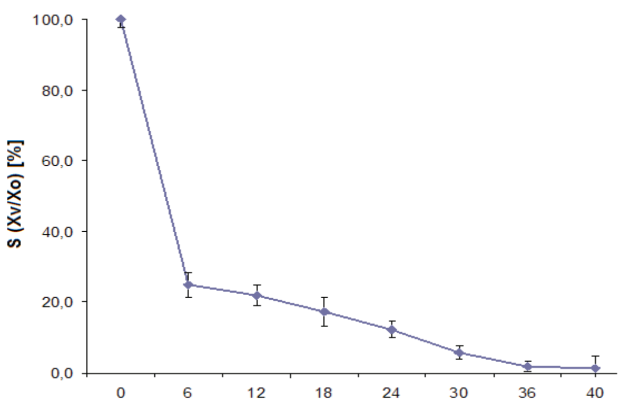

Figure 4. First viability study carried out for batch preheating method

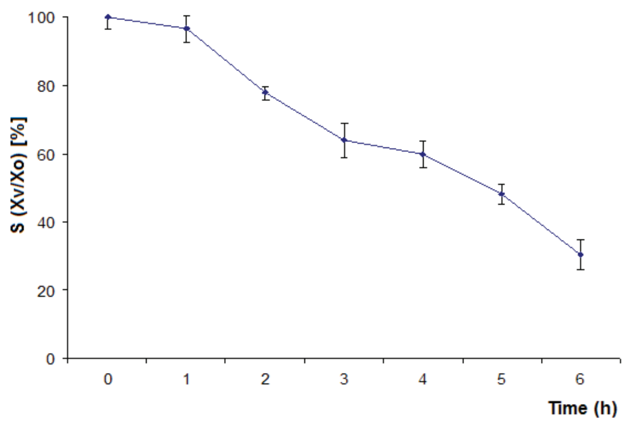

Figure 5. Second viability study carried out for batch preheating method

bacterial cells start an autolysis process and enter into the cellular death phase. This also promotes the generation of insufficient amounts of thermal shock response proteins by the cells, which impedes an adequate response to the high temperatures usually applied during the drying process. This phenomenon can also be observed in Figure 5, where during the first 6 hours of batch preheating method the cell viability decreases about 75% too. Taking into account both results obtained, it can be concluded that the batch preheating method is not adequate to be used prior to the spray drying process since the cell viability of the preheated bio-formulate is reduced way more than 20%, which is the limit value established by the internal quality standards of the CIGB to classify this process stream as adequate prior to being fed to the spray dryer.

Viability test results obtained for continuous preheating process using the tubular heat exchanger

Table 4 shows the results obtained for the cell viability tests carried out for the bio-formulate both at the inlet and outlet of the tubular heat exchanger, while an statistical summary of the viability results obtained at those points are observed in Table 5.

Analyzing the results showed in both tables it can be concluded that the continuous preheating process don't reduces the cell viability of the bio-formulate, since it's not observed a decrease in the value of this parameter at the outlet of the tubular heat exchanger. This is due, fundamentally, to the low retention times experimented by the bio-formulate when flowing inside the heat exchanger (about 5-7 seconds), which reduces the exposition time of the cells to the preheating temperature, thus reducing the probable occurrence of cell stress processes and then autolysis.

According to that, the increased velocity of the continuous preheating process has positive influence on the cell viability results obtained for the bio-formulate.

Comparison of the cell viability results obtained for the dehydrated powder in both preheating methods evaluated

Table 6 shows a comparison between the cell viability results obtained for the dehydrated powder for the two preheating methods considered, while Table 7 shows a statistical summary about the cell viability results obtained for the dehydrated powder also for both preheating methods assessed.

Taking into account the values showed in Table 6, the average cell viability obtained for the dehydrated powder is about 1.37 times higher when applying the continuous preheating method, compared with the value obtained of this parameter when using the batch preheating method. This is because there is no significant reduction of the bio-formulate cell viability during continuous preheating method by using the proposed tubular heat exchanger. That is, the cell viability of the bio-formulate is kept almost constant during continuous preheating method, which doesn't occur in the batch preheating method where the cell viability of the bio-formulate is reduced by near 75% in the first 6 hours of preheating. This has a strong influence on the low values of cell viability further obtained for the dehydrated powder at the outlet of the spray dryer. The later corroborate that the high velocity at which the continuous preheating method takes place affects positively

Table 4. Cell viability results obtained for the bio-formulate both at the inlet and outlet of the tubular heat exchanger

Run	Cell viability (CFU/mL)		Log viability	
	Inlet	Outlet	Inlet	Outlet
1	$5{,}0\cdot10^{11}$	$5{,}0\cdot10^{11}$	11,6990	11,7076
2	$4{,}9\cdot10^{11}$	$4{,}9\cdot10^{11}$	11,6902	11,6902
3	$4{,}8\cdot10^{11}$	$4{,}8\cdot10^{11}$	11,6812	11,6721
4	$5{,}0\cdot10^{11}$	$4{,}9\cdot10^{11}$	11,6990	11,6902
5	$4{,}7\cdot10^{11}$	$4{,}7\cdot10^{11}$	11,6721	11,6721
6	$4{,}9\cdot10^{11}$	$5{,}0\cdot10^{11}$	11,6902	11,6990
7	$4{,}8\cdot10^{11}$	$4{,}8\cdot10^{11}$	11,6812	11,6990
8	$5{,}0\cdot10^{11}$	$5{,}0\cdot10^{11}$	11,6990	11,6812
Average	$4{,}89\cdot10^{11}$	$4{,}89\cdot10^{11}$	11,689	11,689

Table 5. Statistical resume of the cell viability results obtained for the bio-formulate both at the tubular heat exchanger inlet and outlet

Variable	Inlet	Outlet
Frequency	8	8
Mean	11,689	11,689
Variance	0,000101453	0,000168694
Typical Deviation	0,0100724	0,0129882
Minimum	11,6721	11,6721
Maximum	11,699	11,7076
Range	0,0269	0,0355
Asymmetry	–0,591	–0,142962
Curtosis	–0,543436	–0,699992

Table 6. Cell viability results obtained for the dehydrated powder for both preheating methods

Run	Cell viability (CFU/mL)		Log viability	
	Batch	Continuous	Batch	Continuous
1	$3.3\cdot10^{12}$	$4.7\cdot10^{12}$	12.5185	12.6721
2	$3.5\cdot10^{12}$	$4.8\cdot10^{12}$	12.5441	12.6812
3	$3.8\cdot10^{12}$	$4.9\cdot10^{12}$	12.5798	12.6902
4	$3.6\cdot10^{12}$	$4.9\cdot10^{12}$	12.5563	12.6902
5	$3.4\cdot10^{12}$	$5.0\cdot10^{12}$	12.5315	12.6990
6	$3.6\cdot10^{12}$	$4.9\cdot10^{12}$	12.5563	12.6902
7	$3.5\cdot10^{12}$	$4.8\cdot10^{12}$	12.5441	12.6812
8	$3.8\cdot10^{12}$	$4.9\cdot10^{12}$	12.5798	12.6902
Average	$3.56\cdot10^{12}$	$4.86\cdot10^{12}$	12.5513	12.6868

Table 7. Statistical resume about the cell viability results obtained for the dehydrated powder for both preheating methods evaluated

Variable	Inlet	Outlet
Frequency	8	8
Mean	12.5513	12.6868
Variance	0.000463723	0.0000676984
Typical Deviation	0.0215342	0.0082279
Minimum	12.5185	12.6721
Maximum	12.5798	12.699
Range	0.0613	0.0269
Asymmetry	0.0606095	–0.606867
Curtosis	–0.40136	0.249327

the results of cell viability obtained during later process operations, in this case the spray drying step.

Comparison of the costs obtained due to electricity and reagents consumption for both preheating methods evaluated

Tables 8 and 9 describe the cost results obtained due to electricity and reagents consumption, respectively, for both preheating methods evaluated.

According to the results showed in Table 8, it can be observed that the cost results obtained due to electricity consumption for the batch preheating method are about 1.4 times higher in comparison with the results obtained for the continuous process. This is because this method uses a higher amount of equipment functioning longer times. Finally, the costs due to reagent consumption are approximately 3 times higher for the batch preheating method as compared with the continuous process using the tubular heat exchanger. This is owing to, fundamentally, the use of a higher quantity of equipment, hoses and accessories in the batch preheating method, which then need to be washed and sanitized once finished the preheating process in order to be used in the next batch. In this sense, greater amounts of equipment used during preheating method will lead to greater amounts of reagents consumed to sanitize and clean them.

Table 8. Costs results obtained due to electricity consumption for both preheating methods

	Batch		
Equipment	Time (h)	Nominal power (kW)	Cost ($/batch)
Peristaltic pump 1	8	0.85	8.16
Peristaltic pump 2	7	0.85	7.14
Water bath	7	1.20	10.08
Jacketed tank (20 L)	7	0.85	7.14
Jacketed tank (250 L)	8	2.20	21.12
Screw pump	8	2.20	21.12
Total			74.76
	Continuous		
Equipment	Time (h)	Nominal power (kW)	Cost ($/batch)
Peristaltic pump	6	0.85	6.12
Water bath	6	1.20	8.64
Jacketed tank (250 L)	7	2.20	18.48
Screw pump	8	2.20	21.12
Total			54.36

Table 9. Costs results obtained due to reagents consumption for both preheating methods

	Batch		
Equipment	Reagent consumption	Unit cost	Cost ($/batch)
Sodium hydroxide	80 g	$ 0.054/kg	0.004
o-Phosphoric acid	30 mL	$ 0.2352/L	0.007
Water	60 L	$ 0.05/L	3.000
Total			3.011
	Continuous		
Equipment	Reagent consumption	Unit cost	Cost ($/batch)
Sodium hydroxide	40 g	$ 0.054/kg	0.002
o-Phosphoric acid	15 mL	$ 0.2352/L	0.004
Water	20 L	$ 0.05/L	1.000
Total			1.006

Conclusions

During the batch preheating method, the cell viability of the bio-formulate is reduced about 75% in the first 6 hours.

The application of the continuous preheating method doesn't reduce the cell viability of the preheated bio-formulate prior to being fed to the spray dryer.

The dehydrated powder obtained by applying continuous preheating method had an average cell viability value about 1.37 times higher in comparison with the dehydrated powder obtained by means of batch preheating method.

The costs due to electricity and reagent consumption for the batch preheating method are about 1.4 and 3 times higher, respectively, as compared with the costs obtained for the continuous preheating process.

It's feasible to implement, from the techno-economic point of view, the tubular heat exchanger during the preheating step, in substitution of the current batch preheating approach.

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