Supplementary material

Model based optimization of energy consumption in milk evaporators

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1. Model inputs for each Case

This section presents the model inputs for each evaporator layout (Case). The model inputs may be parameters or degrees of freedom and are presented in Tables S1-S4.

Table S1. Case 1 model inputs.

Definition	Symbol	Value
Duration of simulation	tf	1 h
Feed mass flowrate	Fa	10,600 kg/h
Feed temperature	Ta	20 °C
Feed mass fraction (water)	wa,w	87.4 wt.%
Feed mass fraction (lactose)	wa,l	4.8 wt.%
Feed mass fraction (protein)	wa,p	3.4 wt.%
Feed mass fraction (fat)	wa,f	4 wt.%
Feed mass fraction (salt)	wa,s	0.4 wt.%
Steam Pressure	Ps	1.5 bar
Steam Temperature	Ts	125 °C
TVR suction ratio	SR	1.1 bar
TVR outlet pressure	Pout	0.35 bar
FFE Vapor friction factor	ff,vap	0.2
Maximum height above plate	hmax	30 cm
Plate diameter	din	2.3 m
Plate thickness	hplate	10 mm

Table S2. Case 2,3 model inputs.

Definition	Symbol	Value
Duration of simulation	tf	1 h
Feed mass flowrate	Fa	1,000 kg/h
Feed temperature	Ta	55 °C
Feed mass fraction (water)	wa,w	87.4 wt.%
Feed mass fraction (lactose)	wa,l	4.8 wt.%
Feed mass fraction (protein)	wa,p	3.4 wt.%
Feed mass fraction (fat)	wa,f	4 wt.%
Feed mass fraction (salt)	wa,s	0.4 wt.%
Steam Pressure	Ps	1.5 bar
Steam Temperature	Ts	128 °C
TVR suction ratio	SR	1.1 bar
TVR outlet pressure	Pout	0.35 bar
FFE Vapor friction factor	ff,vap	0.2
Maximum height above plate	hmax	25 mm
Plate diameter	din	1.3 m
Plate thickness	hplate	10 mm
Plate surface roughness	rplate	10 μm
Number of liquid holes	Nliq hole	100
Diameter of liquid holes	dliq hole	5 mm
Diameter of evaporator body	dout	1.4 m
Height of outer rim	hrim	40 mm
Number of evaporator tubes	N	35
Tube inner diameter	Di	0.0508 m
Tube length	L	6 m
Overall heat transfer coefficient (evaporator body)	U	2500 $J \cdot m^{-2} s^{-1} °C^{-1}$
Number of preheater tubes	Npt	1
Diameter of preheater tube	Dpt	30 mm
Length of preheater tubes	Lpt	1 m
Overall heat transfer coefficient (preheater tubes)	Upt	3000 $J \cdot m^{-2} s^{-1} °C^{-1}$

Table S3. Case 4 model inputs.

Definition	Symbol	Value
Duration of simulation	tf	1 h
Feed mass flowrate	Fa	1,000 kg/h
Feed temperature	Ta	50 °C
Feed mass fraction (water)	wa,w	87.4 wt.%
Feed mass fraction (lactose)	wa,l	4.8 wt.%
Feed mass fraction (protein)	wa,p	3.4 wt.%
Feed mass fraction (fat)	wa,f	4 wt.%
Feed mass fraction (salt)	wa,s	0.4 wt.%
MVR compression ratio	CR	1.4
MVR mechanical efficiency	em	0.5
FFE Vapor friction factor	ff,vap	0.2
Maximum height above plate	hmax	25 mm
Plate diameter	din	1.3 m
Plate thickness	hplate	10 mm
Plate surface roughness	rplate	10 μm
Number of liquid holes	Nliq hole	100
Diameter of liquid holes	dliq hole	5 mm
Diameter of evaporator body	dout	1.4 m
Height of outer rim	hrim	40 mm
Number of evaporator tubes	N	35
Tube inner diameter	Di	0.0508 m
Tube length	L	6 m
Overall heat transfer coefficient (evaporator body)	U	2500 $J \cdot m^{-2} s^{-1} °C^{-1}$

Table S4. Case 5 model inputs.

Definition	Symbol	Value
Duration of simulation	tf	1 h
Feed mass flowrate	Fa	16,000 kg/h
Feed temperature	Ta	55 °C
Feed mass fraction (water)	wa,w	87.4 wt.%
Feed mass fraction (lactose)	wa,l	4.9 wt.%
Feed mass fraction (protein)	wa,p	3.5 wt.%
Feed mass fraction (fat)	wa,f	3.5 wt.%
Feed mass fraction (minerals)	wa,m	0.7 wt.%
Steam Pressure	Ps	3 bar
Steam Temperature	Ts	133 °C
TVR suction ratio	SR	0.5
TVR outlet pressure	Pout	0.35 bar
FFE Vapor friction factor	ff,vap	0.2
Maximum height above plate	hmax	0.4 m
Plate diameter	din	2.3 m
Plate thickness	hplate	10 mm
Plate surface roughness	rplate	10 μm
Number of liquid holes	Nliq hole	150
Diameter of liquid holes	dliq hole	5 mm
Diameter of evaporator body	dout	2.4 m
Height of outer rim	hrim	40 mm
Number of evaporator tubes	N	100/131/111/264
Tube inner diameter	Di	0.0508 m
Tube length	L	10 m
Overall heat transfer coefficient (evaporator body)	U	2500 $J \cdot m^{-2} s^{-1} °C^{-1}$
Split fraction	SF	0.4

2. GSA factors for each Case

This section provides a detailed description of the factors used in the Global System Analysis (GSA) for each studied Case. The Factors are described in Tables S5-S8. Along with their lower and upper bounds and the assigned probability distribution.

Table S5. Uncertainty analysis factors – Case 1.

Variable name	Unit	Lower bound	Upper bound	Probability distribution
TVR – Pressure (discharge)	bar	0.3	0.35	Uniform distribution
TVR – Suction ratio	-	0.4	2	Uniform distribution
Feed Temperature	°C	40	60	Uniform distribution

Table S6. Uncertainty analysis factors – Cases 2 and 3.

Variable name	Unit	Lower bound	Upper bound	Probability distribution
TVR – Pressure (discharge)	bar	0.3	0.35	Uniform distribution
TVR – Suction ratio	-	0.4	2	Uniform distribution
Feed Temperature	°C	40	60	Uniform distribution

Table S7. Uncertainty analysis factors – Case 4.

Variable name	Unit	Lower bound	Upper bound	Probability distribution
MVR – Compression ratio	-	1	1.4	Uniform distribution
Feed Temperature	°C	40	60	Uniform distribution

Table S8. Uncertainty analysis factors – Case 5.

Variable name	Unit	Lower bound	Upper bound	Probability distribution
Split fraction	-	0.4	0.7	Uniform distribution
TVR – Suction ratio	-	0.4	0.8	Uniform distribution
Feed Temperature	°C	40	70	Uniform distribution

3. Dynamic optimization decision variables for each Case

This section contains details about the optimization variables selected for the dynamic optimization of each studied layout. Tables S9-S11 showcase the control variables, a range of acceptable values as well as type of the acceptable values for each optimization scenario.

Table S9. optimization variables specifications – Case 1.

Variable name	Unit	Lower bound	Upper bound	Type/Allowable values
Scenario 1,2,3,4,6				
TVR – Pressure (discharge)	bar	0.3	0.35	Time invariant/ Continuous
TVR – Suction ratio	-	0.4	2	Time invariant/ Continuous
Feed Temperature	°C	20	60	Time invariant/ Continuous
Scenario 5				
FFE1 tube inner diameter	m	0.0254	0.0508	Time invariant/ Enumerated
FFE1 tube length	m	5	20	Time invariant/ Continuous
FFE2 tube inner diameter	m	0.0254	0.0508	Time invariant/ Enumerated
FFE2 tube length	m	5	20	Time invariant/ Continuous

Table S10. Optimization variables specifications – Case 2,3.

Variable name	Unit	Lower bound	Upper bound	Type/Allowable values
Scenario 1,2,3,4,6				
TVR – Pressure (discharge)	bar	0.3	0.35	Time invariant/ Continuous
TVR – Suction ratio	-	0.4	2	Time invariant/ Continuous
Feed Temperature	°C	40	60	Time invariant/ Continuous
Scenario 5				
FFE1 tube inner diameter	m	0.0254	0.0508	Time invariant/ Enumerated
FFE1 tube length	m	0.5	10	Time invariant/ Continuous
FFE2 tube inner diameter	m	0.0254	0.0508	Time invariant/ Enumerated
FFE2 tube length	m	0.5	10	Time invariant/ Continuous

Table S11. Optimization variables specifications – Case 4.

Variable name	Unit	Lower bound	Upper bound	Type/Allowable values
Scenario 1,2,3,4,6				
MVR – Adiabatic efficiency	-	0.2	1	Time invariant/ Continuous
MVR – Compression ratio	-	1	1.45	Time invariant/ Continuous
Feed Temperature	°C	40	60	Time invariant/ Continuous
Scenario 5				
FFE1 tube inner diameter	m	0.0254	0.0508	Time invariant/ Enumerated
FFE1 tube length	m	0.5	10	Time invariant/ Continuous