**Supplementary material**

**Model based optimization of energy consumption in milk evaporators**

**Artemis Tsochatzidi 1, Achilleas L. Arvanitidis 1 and Michael C. Georgiadis 1,\***

1 Department of Chemical Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

\*Correspondence: mgeorg@auth.gr

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 |
| Νumber 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·m-2s-1K-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·m-2s-1K-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 |
| Νumber 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·m-2s-1K-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 |
| Νumber 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·m-2s-1K-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 – Case 2,3.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **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 |
| ΜVR – 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 |