International Journal of Innovation in
Mechanical Engineering and Advanced Materials
Journal homepage: publikasi.mercubuana.ac.id/index.php/ijimeam
Vol. 8 (No. 3), 2026, Art. No. 39654, pp. 191-205
DOI: 10.22441/ijimeam.v8i3.39654

Supplementary Document

Comparative Assessment of Industrial Heat Pump Configurations for Spray Drying Dairy Manufacturing

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Supplementary Material

State points of every heat pump stage and of the MVR (Tables S2–S6), the full 36-case sensitivity grid for C3 and C4 (Table S1) and the cycle COP as a function of compressor isentropic efficiency (Table S7). Section, table and equation numbers refer to the main manuscript.

Table S1. 36-case grid of ψ for C3 (independent model) and C4 over stage-1 COP, stage-2 COP and the share f_4 of steam served at 4 barg (design-point basis).

COP stage 1	COP stage 2	f_4	ψ C3 (%)	ψ C4 (%)	C4 – C3 (points)	Electricity C3 (kW)	Electricity C4 (kW)	ΔQwaste needed by C3 (kW)
1.683	2.200	0.700	31.6	40.4	8.8	1,733	2,473	0
1.683	2.200	0.825	33.3	40.4	7.2	1,994	2,473	0
1.683	2.200	1.000	36.0	40.4	4.4	2,358	2,473	0
1.683	2.625	0.700	32.6	42.2	9.7	1,653	2,368	0
1.683	2.625	0.825	34.5	42.2	7.7	1,899	2,368	0
1.683	2.625	1.000	37.9	42.2	4.4	2,243	2,368	0
1.683	2.700	0.700	32.7	42.5	9.8	1,641	2,353	0
1.683	2.700	0.825	34.7	42.5	7.8	1,885	2,353	0
1.683	2.700	1.000	38.1	42.5	4.4	2,227	2,353	0
1.683	3.200	0.700	33.5	44.1	10.6	1,578	2,270	0
1.683	3.200	0.825	35.8	44.1	8.3	1,810	2,270	0
1.683	3.200	1.000	39.8	44.1	4.3	2,136	2,270	0
2.500	2.200	0.700	35.2	47.6	12.4	1,448	2,099	0
2.500	2.200	0.825	38.2	47.6	9.5	1,657	2,099	0
2.500	2.200	1.000	43.6	47.6	4.0	1,921	2,099	137
2.500	2.625	0.700	36.9	51.6	14.7	1,328	1,901	0
2.500	2.625	0.825	40.7	51.6	10.9	1,509	1,901	35
2.500	2.625	1.000	48.0	51.6	3.6	1,705	1,901	353
2.500	2.700	0.700	37.2	52.2	15.0	1,311	1,873	0
2.500	2.700	0.825	41.1	52.2	11.2	1,483	1,873	61
2.500	2.700	1.000	48.7	52.2	3.5	1,674	1,873	384
2.500	3.200	0.700	38.7	55.9	17.2	1,218	1,717	0
2.500	3.200	0.825	43.4	55.9	12.5	1,343	1,717	201
2.500	3.200	1.000	52.9	55.9	3.1	1,504	1,717	554
3.500	2.200	0.700	37.7	52.4	14.7	1,279	1,865	0
3.500	2.200	0.825	41.5	52.4	10.9	1,453	1,865	91
3.500	2.200	1.000	48.4	52.4	4.0	1,687	1,865	371
3.500	2.625	0.700	40.0	57.3	17.2	1,135	1,667	42
3.500	2.625	0.825	44.6	57.3	12.6	1,275	1,667	269

COP stage 1	COP stage 2	f_4	ψ C3 (%)	ψ C4 (%)	C4 – C3 (points)	Electricity C3 (kW)	Electricity C4 (kW)	ΔQwaste needed by C3 (kW)
3.500	2.625	1.000	53.8	57.3	3.5	1,470	1,667	588
3.500	2.700	0.700	40.3	58.0	17.7	1,113	1,638	64
3.500	2.700	0.825	45.1	58.0	12.9	1,249	1,638	295
3.500	2.700	1.000	54.7	58.0	3.3	1,439	1,638	619
3.500	3.200	0.700	42.2	62.6	20.5	994	1,483	183
3.500	3.200	0.825	47.9	62.6	14.7	1,109	1,483	435
3.500	3.200	1.000	60.0	62.6	2.6	1,269	1,483	789

Table S2. C1 preheater, R134a (evaporation 1 °C, 3.04 bar; condensation 80 °C, 26.33 bar; subcooled to 30 °C; $\dot{m}_r$ = 1.021 kg/s for 232.4 kW).

State	P (bar)	T (°C)	h (kJ/kg)	s (kJ/kg·K)
1 compressor inlet (5 K superheat)	3.04	6.0	403.68	1.743
2s isentropic	26.33	–	449.55	1.743
2 actual	26.33	106.7	469.22	1.796
3 condenser outlet	26.33	30.0	241.72	1.138
4 after valve	3.04	1.0	241.72	1.152

Table S3. C2 SHC-HP, R1233zd(E) (evaporation 1 °C, 0.507 bar; condensation 90 °C, 8.35 bar; subcooled to 75 °C; $\dot{m}_r$ = 5.79 kg/s for 1,100 kW).

State	P (bar)	T (°C)	h (kJ/kg)	s (kJ/kg·K)
1 compressor inlet	0.507	6.0	407.26	1.756
2s isentropic	8.35	–	459.15	1.756
2 actual	8.35	108.9	481.39	1.816
3 condenser outlet	8.35	75.0	291.40	1.293
4 after valve	0.507	1.0	291.40	1.333

Table S4. Stage 1, transcritical CO_2 with internal heat exchanger (evaporation 0 °C, 34.85 bar; gas cooler 224 bar, outlet 90 °C; IHX effectiveness 0.8; $\dot{m}_r$ = 5.20 kg/s in C4 and 4.69 kg/s in C3).

State	P (bar)	T (°C)	h (kJ/kg)	s (kJ/kg·K)
1′ evaporator outlet	34.85	5.0	439.59	1.877
1 compressor inlet (after IHX)	34.85	71.0	520.78	2.141
2s isentropic	224	–	653.88	2.141
2 actual	224	290.5	710.92	2.246
3 gas-cooler outlet	224	90.0	390.83	1.526
3′ after IHX	224	55.8	309.63	1.292
4 after valve	34.85	0.0	309.63	1.401

Table S5. Stage 2, HFO-1336mzz(Z) (evaporation 85 °C, 4.89 bar; condensation 157 °C, 22.51 bar; $\dot{m}_r$ = 34.8 kg/s in C4 and 31.4 kg/s in C3; minimum pinch against steam generation 5.06 K).

State	P (bar)	T (°C)	h (kJ/kg)	s (kJ/kg·K)
1 compressor inlet	4.89	90.0	449.46	1.737
2s isentropic	22.51	–	470.07	1.737
2 actual	22.51	157.0 (two-phase, x = 0.92)	478.90	1.757
3 condenser outlet	22.51	149.0	401.63	1.577
4 after valve	4.89	85.0	401.63	1.603

Table S6. MVR and desuperheater (design point, 4,000 kg/h of delivered steam). Specific enthalpies are tabulated; the corresponding specific entropies are s_1 = 6.820 kJ/kg·K (state 1; $s_{2s} = s_1$), s_2 = 6.976

kJ/kg·K (state 2), 0.367 kJ/kg·K (spray water) and 6.493 kJ/kg·K (state 3). The MVR steam flow is 1.017 kg/s (3.66 t/h) and the spray-water flow is 0.094 kg/s (0.34 t/h).

State	Fluid	P (bar)	T (°C)	h (kJ/kg)
1 MVR inlet, saturated steam	H_2O	5.013	151.9	2,748.2
2s isentropic outlet	H_2O	13.013	–	2,948.3
2 actual outlet (ηis 0.70)	H_2O	13.013	295.6	3,034.1
Spray water	H_2O	13.013	25.0	104.8
3 delivered steam, saturated	H_2O	13.013	191.7	2,786.5

Table S7. Cycle COP as a function of the compressor isentropic efficiency.

ηis	0.65	0.70	0.75	0.80
COP C1 (R134a)	3.30	3.47	3.65	3.82
COP C2 (R1233zd(E))	2.45	2.56	2.67	2.79
COP stage 1 (CO_2, with IHX)	1.64	1.68	1.73	1.78
COP stage 2 (HFO)	2.51	2.62	2.74	2.79

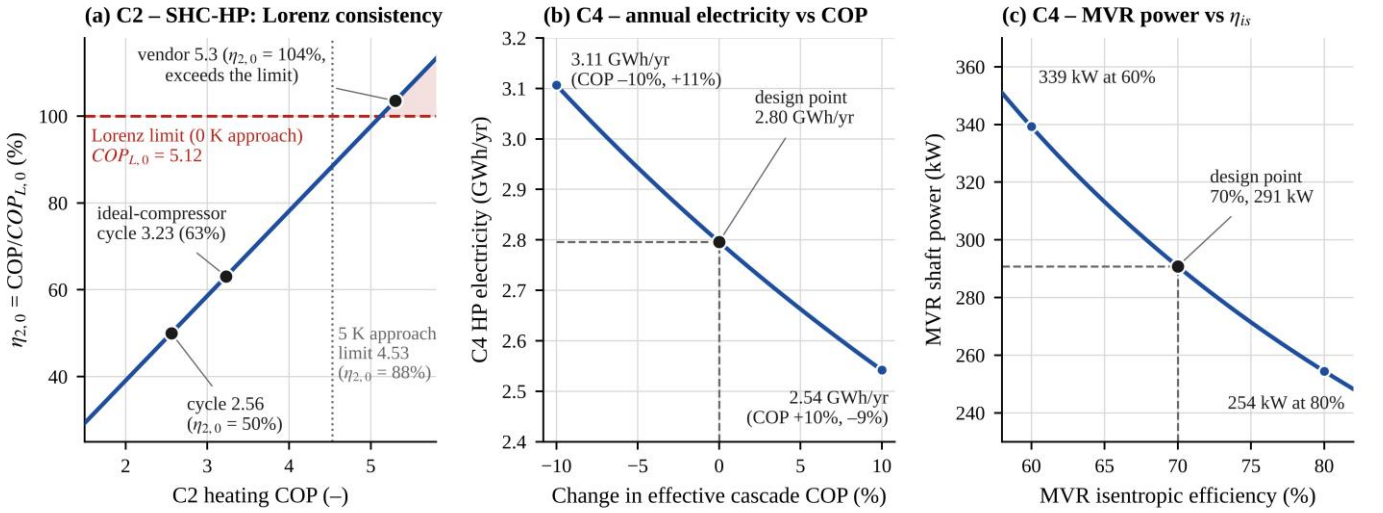


Figure S1. One-at-a-time sensitivity: (a) Lorenz-limit consistency of the C2 (SHC-HP) heating COP; (b) annual electricity of C4 versus effective cascade COP; (c) MVR shaft power versus isentropic efficiency. Dashed lines mark the design points (Tables 7, 6 and 2 of the main manuscript, respectively).