Second-Law Analysis of a Cascade Joule-Thompson Microcooler
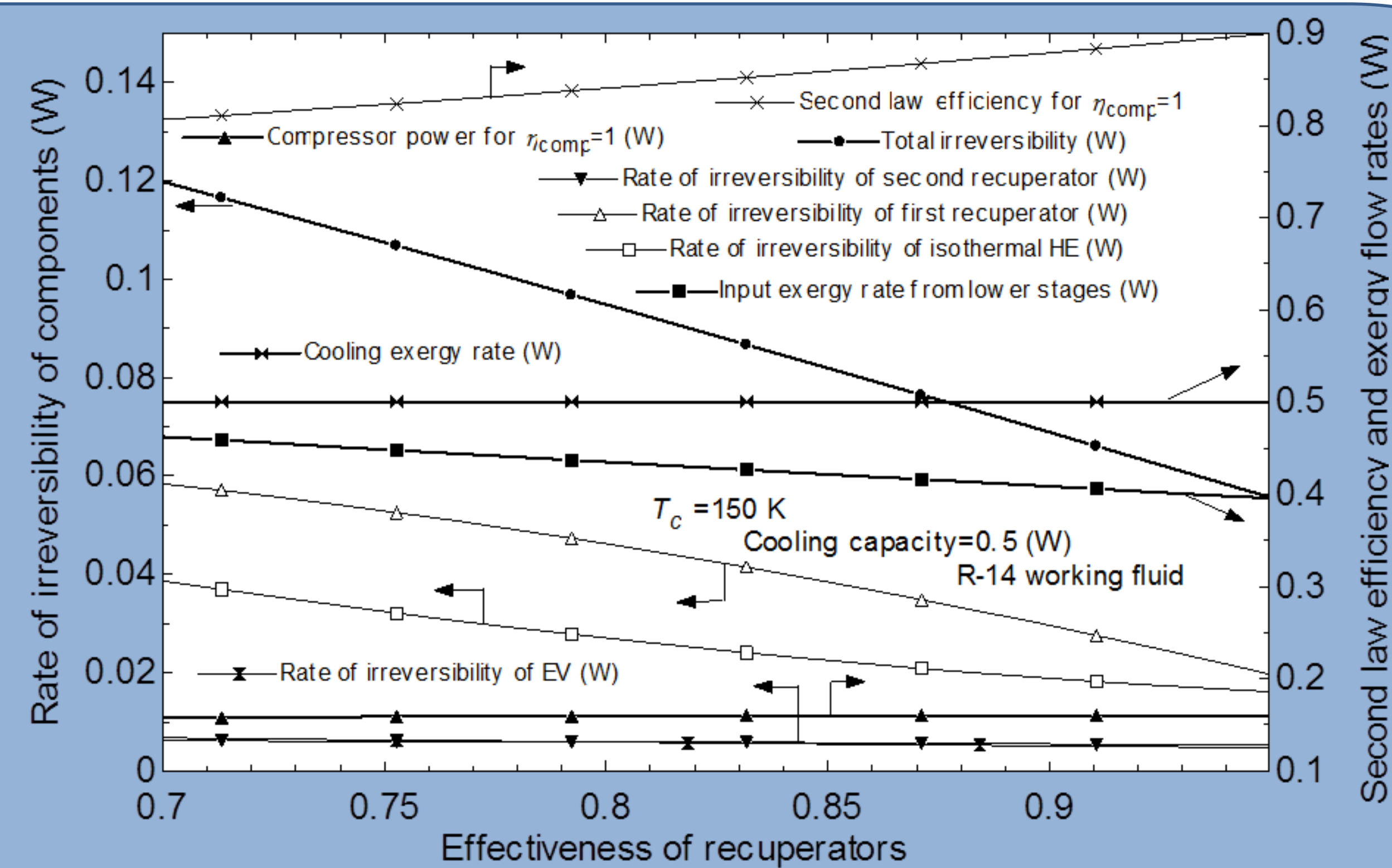
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Abstract

Cascade Joule-Thomson Microcoolers have been proposed in literature in which different compressors with low values of pressure ratio of order four using different working fluids are anticipated to drive the microcooler. A cascade of five stages is expected to provide cooling at a load temperature of 150 K. In this study a second-law analysis of such a microcooler is performed to quantify the effect of important design parameters representing the basic components and processes of the microcooler on its performance. The effects of several important design parameters including the effectiveness of all heat exchangers as well as the effect of possible pressure drop in the recuperative heat exchanger on cooling power and the exergetic efficiency of the microcooler are obtained. The inefficiency of the compressors is included using an exergetic efficiency parameter for the compressors. The heat transfer from each stage to other stages is modelled using an effectiveness parameter for the heat exchangers that can be varied to investigate their influence on cooling power and the efficiency of the microcooler.

Results

$T_c = 150$ K
Cooling capacity=0.5 (W)
R-14 working fluid

Model

$$\varepsilon = [h(T_{Le}, P_{Le}) - h(T_{Li}, P_{Li})]/[h(T_{Hi}, P_{Le}) - h(T_{Li}, P_{Li})]$$

$$[h(T_{Hi}, P_{Hi}) - h(T_{He}, P_{He})] = [h(T_{Le}, P_{Le}) - h(T_{Li}, P_{Li})]$$

$$\varepsilon_{iso.H} = (T_{Hi} - T_{He})/(T_{Hi} - T_{iso})$$

$$\varepsilon_{iso.L} = (T_{Le} - T_{Li})/(T_{iso} - T_{Li})$$

$$\dot{I} = \sum_i \dot{m}_i e_i - \sum_i \dot{m}_e e_e - \dot{W} + (1 - \frac{T_0}{T})\dot{Q}$$
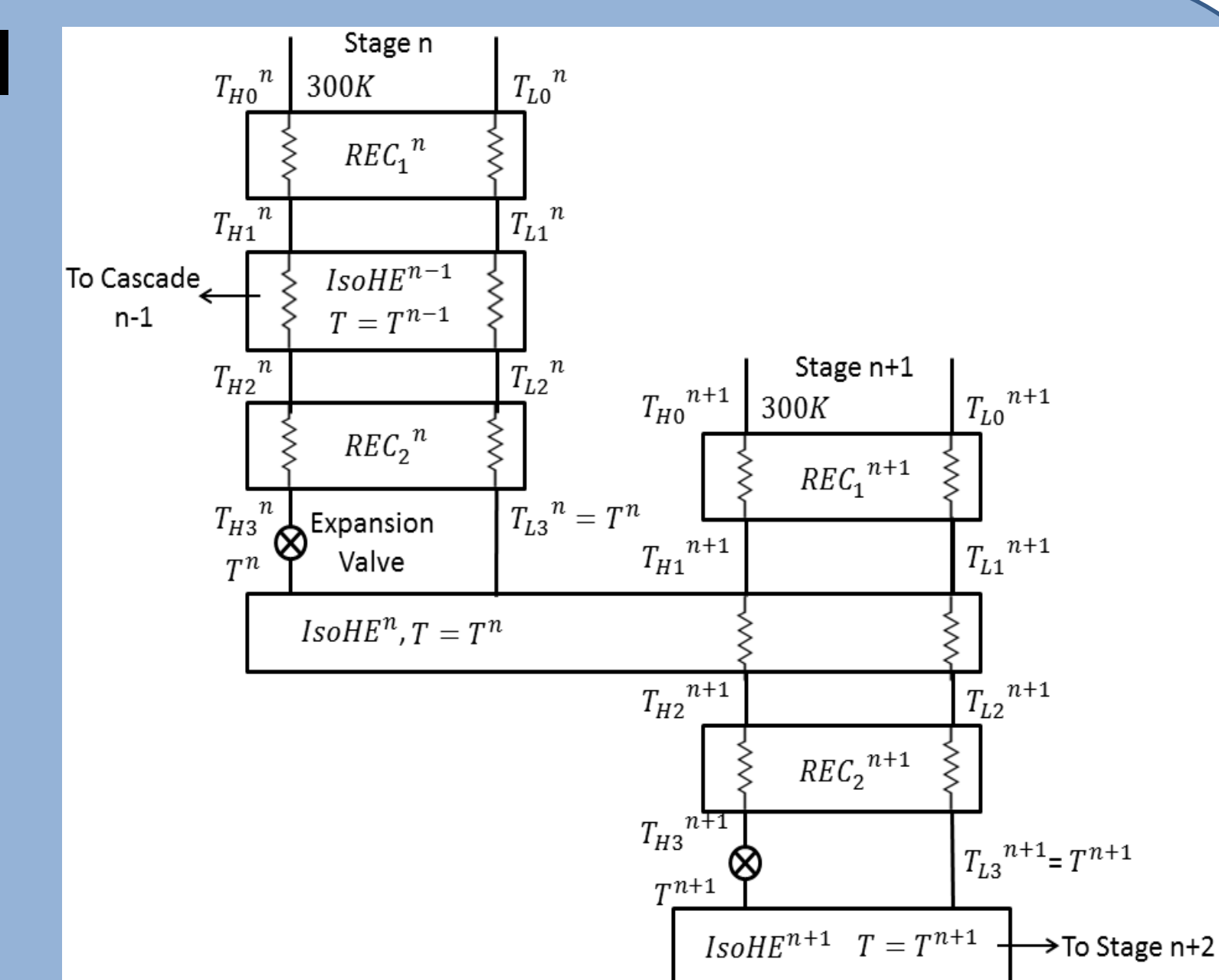
$$e = (h - h_0) - T_0(s - s_0)$$

$$\dot{i}_{rec} = \dot{m}\{[h(T_{Hi}, P_{Hi}) - h(T_{He}, P_{He})] + [h(T_{Li}, P_{Li}) - h(T_{Le}, P_{Le})]\} - \dot{m}T_0\{[s(T_{Hi}, P_{Hi}) - s(T_{He}, P_{He})] + [s(T_{Li}, P_{Li}) - s(T_{Le}, P_{Le})]\}$$

$$\dot{i}_{EV} = \dot{m}T_0[s(T_{Hi}, P_{Hi}) - s(x_{Le}, T_{Le})]$$

$$\eta_{comp} = (e_e - e_i)/w_{comp}$$

Quantity (units)	Effectiveness of recuperators for each stage in the cascade of five stages				
	ε=0.75	ε=0.8	ε=0.85	ε=0.9	ε=0.95
Cooling load; stage 1 (W)	0.7004	0.6498	0.6030	0.5595	0.5192
Cooling load; stage 2 (W)	0.6920	0.6424	0.5965	0.5538	0.5142
Cooling load; stage 3 (W)	0.6239	0.5949	0.5670	0.5401	0.5143
Cooling load; stage 4 (W)	0.5806	0.5629	0.5454	0.5282	0.5113
Cooling load; stage 5 (W)	0.5000	0.5000	0.5000	0.5000	0.5000
Mass flow rate; stage 1 (mg/s)	2.173	1.997	1.835	1.686	1.550
Mass flow rate; stage 2 (mg/s)	1.778	1.641	1.515	1.399	1.291
Mass flow rate; stage 3 (mg/s)	6.350	5.983	5.635	5.306	4.994
Mass flow rate; stage 4 (mg/s)	1.307	1.262	1.218	1.175	1.133
Mass flow rate; stage 5 (mg/s)	4.193	4.172	4.151	4.130	4.110
Quality after expansion; stage 1	0.1199	0.1113	0.1027	0.0941	0.0855
Quality after expansion; stage 2	0.0868	0.08150	0.0761	0.0708	0.0655
Quality after expansion; stage 3	0.1561	0.1459	0.1357	0.1255	0.1153
Quality after expansion; stage 4	0.0794	0.0758	0.0722	0.0686	0.0650
Quality after expansion; stage 5	0.1017	0.0970	0.0925	0.08790	0.0834
Total input power; all stages with η_{comp}=1 (W)	0.7360	0.711	0.6787	0.6484	0.6194
Second law efficiency; all stages with η_{comp}=1	0.6793	0.7042	0.7367	0.7740	0.8073

Conclusions

- The recuperator losses are important, but their effect on the efficiency of the microcooler is not very significant.

- The most important parameter influencing the second law efficiency of the microcooler is the exergetic efficiency of the compressor.

- The effects of several important design parameters, including the effectiveness of all heat exchangers as well as the effect of possible pressure drop in the recuperative heat exchanger, on cooling power and the exergetic efficiency of the microcooler are obtained. It was shown that not only are the recuperator losses important for the performance of the stage but that they also influence the exergy input required from the stages upstream that are necessary for the successful operation of the fifth stage.

- Assuming a second law efficiency of 0.1 for the compressors at each stage and including the internal irreversibility of the cold head, the second law efficiency of the cascade J-T microcooler is estimated to be 10 percent.