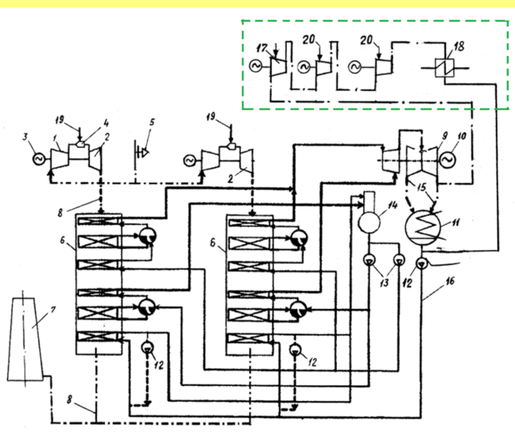
# Energy Efficiency Enhancement of CCGT-200 Units via Multi-stage R718 Heat Pumps

**Kuat Baubekov**

**S. Seifullin Kazakh Agrotechnical Research University**

## Introduction & Motivation

Challenge: Up to 50% of fuel energy is lost in CCGT condensers.
Objective: Thermodynamic justification of heat recovery into the cycle.
Solution: High-temperature heat pumps using R718 (Water) as a natural refrigerant.



Components:
1–4: Gas turbine topping cycle;
6: HRSG;
9: Steam turbine;
11: Condenser;
17: Multi-stage steam compressor;
18: Network heat exchanger;
20: Interstage cooling via water injection.

**Figure 1.** Principal thermal scheme of the CCGT-200 unit integrated with a multi-stage R718 heat pump cycle.

Integration of a 3-stage Mechanical Vapor Recompression (MVR) system directly into the steam turbine exhaust. Interstage water injection is used to control superheating.

## Thermodynamic Phenomenon

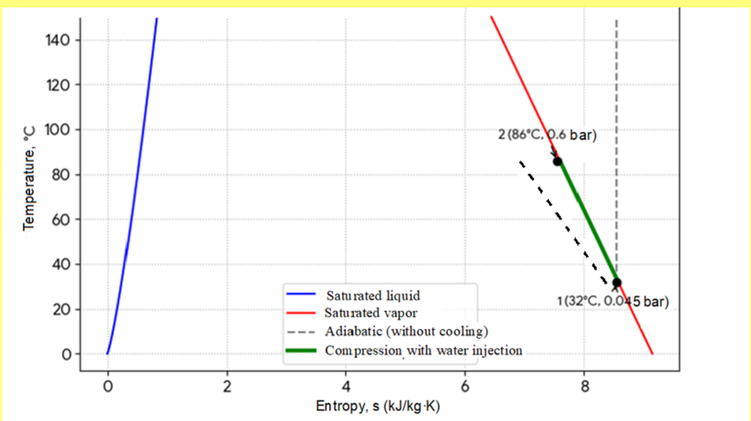



Figure 2. Comparative T-s diagram: Adiabatic compression without cooling (dashed line) vs. proposed multi-stage cycle with water injection (solid line).

Strategy A (Dashed line): Conventional adiabatic compression.

Strategy B (Solid line): Proposed multi-stage cycle with water injection keeping the process near the saturation line.

**Table 1.** Comparative Analysis of R-718 Compression Efficiency at Different Discharge Pressures

| $P_{out}$, bar | $T_{st.sat}$,°C | Compression ratio, $\pi$ | Theoretical COP | *Real COP ($\eta_{eff}$= 0.318) | Power consumption (N), MW |
|---|---|---|---|---|---|
| 0.1 | 45.8 | 2.2 | 72.27 | 25.0 | 5.3 |
| 0.3 | 69.1 | 6.7 | 34.5 | 18.0 | 7.4 |
| **0.6** | **86.0** | **13.3** | **24.8** | **12.5** | **10.4** |
| 6.0 | 158.8 | 133.3 | 12.3 | 3.5 | 33.0 |

*Note: The value of ($\eta_{eff}$=0.318) is a conservative estimate for vacuum R718 cycles, derived from the thermodynamic constraints and loss analyses (discussed in A. Kiliscarslan and N. Mueller, Zühlsdorf B., Schlemminger C., Bantle M., Hafner A., Ommen T.S., Jensen J.K., Elmegaard B.).

## Performance & Results

**Table 2.** Performance Comparison: Single-stage vs. Three-stage R-718 Recompression (0.1–0.6 bar)

| Parameter | Single-stage | *3-stage (Proposed) | Change, % |
|---|---|---|---|
| Pressure ratio per stage (π) | 6.00 | 1.82 | –70% |
| Effective efficiency ($\eta_{eff}$) | 0.318 | 0.58 | +82% |
| Actual power consumption ($N_{real}$), MW | 10.4 | 4.69 | **–55%** |
| Coefficient of Performance (COP) | 12.5 | **27.7** | 2.2x increase |
| Net $CO_2$ Reduction, tons/year | — | 110,400 | — |
| Annual Economic Effect, USD | — | $5.15 million | — |

*Note: The efficiency improvement for the three-stage system is based on the multi-stage R718 architecture principles (established in M. Bantle and B. Zühlsdorf, G. Madirazza and S. Wolf, H. Muller and K. Schmidt).

## Methodology & Principal Scheme

Thermodynamic analysis via Poisson's equation reveals that single-stage compression leads to extreme parasitic superheating (up to 282°C). Transitioning to the proposed 3-stage Strategy B reduces power consumption by **55%**, achieving an exceptional **COP of 27.7**.

**Thermodynamic Phenomenon of R718 Compression**

**The Challenge of Adiabatic Superheating in Vacuum**

**Key Physics:**

- ✓ **Initial state:** $P_1 = 0.045\ bar, T_1 = 32.9$ °C $(306\ K)$
- ✓ **Compression ratio:** $\pi = 13.3$ (from 0.045 to 0.6 bar)
- ✓ **Adiabatic index (k):** 1.3 (for superheated steam).
- ✓ **Degree coefficient:** (k-1)/k = (1.3-1)/1.3 = 0.23

**Calculation (Poisson's Equation) (1):**

$$T_2 = T_1 \cdot \pi^{\frac{k-1}{k}} = 306 \cdot 13.3^{0.23} \approx 555\ K \approx 282\ ^\circ C \quad (1)$$

**Saturation point at 0.6 bar:** $T_{sat} = 86$ °C

**Excessive Superheat:** $\Delta T = 282 - 86 = 196$ °C.

According to Poisson's equation, single-stage compression from 0.045 to 0.6 bar leads to extreme superheating (T2 ≈ 282°C). This "parasitic heat" reduces efficiency and stresses the equipment.

## Economic & Environmental Impact

**Table 3.** Potential Economic Impact for Bulgaria (Case Study: CCGT-450)

| Parameter | CCGT-200 (Article) | **Bulgaria (CCGT-450)** | Unit |
|---|---|---|---|
| Steam mass flow rate | 35.9 | **75.5** | kg/s |
| Discharge temperature (with out cooling) | ~282 | **~290** | °C |
| Working temperature (Strategy B) | 86.0 | **86.0 - 90.0** | °C |
| Annual Natural gas savings | 64.0 | **134.4** | mln m³/year |
| Net Economic Effect | $5.15 mln | **19.8 mln BGN** | per year |
| Emission reduction | 110.4 | **232.0** | thousand tons/year |
| Payback Period | <1 | **<0.8** | year |

## Conclusions

The 3-stage R718 recompression technology is a vital and cost-effective tool for the industry's decarbonization roadmap and energy independence.

## References

1. **Kiliscarslan, A.** A comparative study of water as a refrigerant with some current refrigerants / A. Kiliscarslan, N. Mueller // Applied Thermal Engineering. – 2005. – Vol. 25, iss. 16. – P. 2465–2482. – DOI: 10.1016/j.applthermaleng. 2005.01.015.

2 **Zühlsdorf, B.** Design recommendations for R-718 heat pumps in high temperature applications / B. Zühlsdorf, C. Schlemminger, M. Bantle (et al.) // Proceedings of the 13th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2018). – Valencia, Spain, 2018. – P. 1367–1375. – DOI: 10.18462/iir.gl. 2018.1367.

3. **Lachner, T. J.** The Steam-Compression Cycle / T. J. Lachner, G. F. Nellis, S. A. Klein // International Journal of Refrigeration. – 2007. – Vol. 30, iss. 7. – P. 1252–1261. – DOI: 10.1016/j.ijrefrig.2007.01.011.

4. **Madirazza, G.** Multi-stage centrifugal compressors for water vapor recompression / G. Madirazza, S. Wolf // Journal of Process Engineering. – 2021. – Vol. 14, no. 3. – P. 112–125.

5. **Bantle, M.** Multi-stage high temperature heat pumps with R718 as refrigerant / M. Bantle, B. Zühlsdorf // International Journal of Refrigeration. – 2020. – Vol. 110. – P. 234–242. – DOI: 10.1016/j.ijrefrig.2019.10.021.