Conceptualization of wet and dry steam compression with liquid water injection for high-temperature heat pumps - A thermodynamic approach

Seyed Mojtaba Hosseinnia, Sébastien Poncet, Hakim Nesreddine, Dominique Monney, Canada

Water has been used as a natural, extremely low global warming potential refrigerant in high-temperature heat pumps. The steam compressor's extra high discharge temperature at high-pressure ratios (e.g., 15) can be prevented via liquid water injection during the compression process as an effective desuperheating method. The proposed thermodynamic approach provides insights into the compression process with liquid injection (above and below the saturated vapor line), temperature/pressure build-ups, compression work, and the coefficient of performance of a heat pump equipped with a rotary vane compressor to deliver heat at 200°C.

High-temperature heat pumps (HTHPs) are an effective means to decarbonize the required energy in the industrial sector via electrification. In this context, as an example, they should supply thermal energy at high temperatures, near 200°C. Current low global warming potential refrigerants such as HFOs (e.g., R1336mzz(Z), R1234ze(Z)) and HCFOs (e.g., R1233zd(E)) have basic limitations like (i) their low critical temperatures and the (ii) decomposition of refrigerant/lubrication oil at high temperatures while running for a long time. The mentioned obstacles force the maximum possible temperature reachable by the mentioned refrigerants to 175°C [1]. Water, aka R718, presents excellent properties that makes it unique as a refrigerant to be utilized in a HTHP system: high critical temperature of 373.9°C, large heat of vaporization, low cost, abundant, and non-toxic.

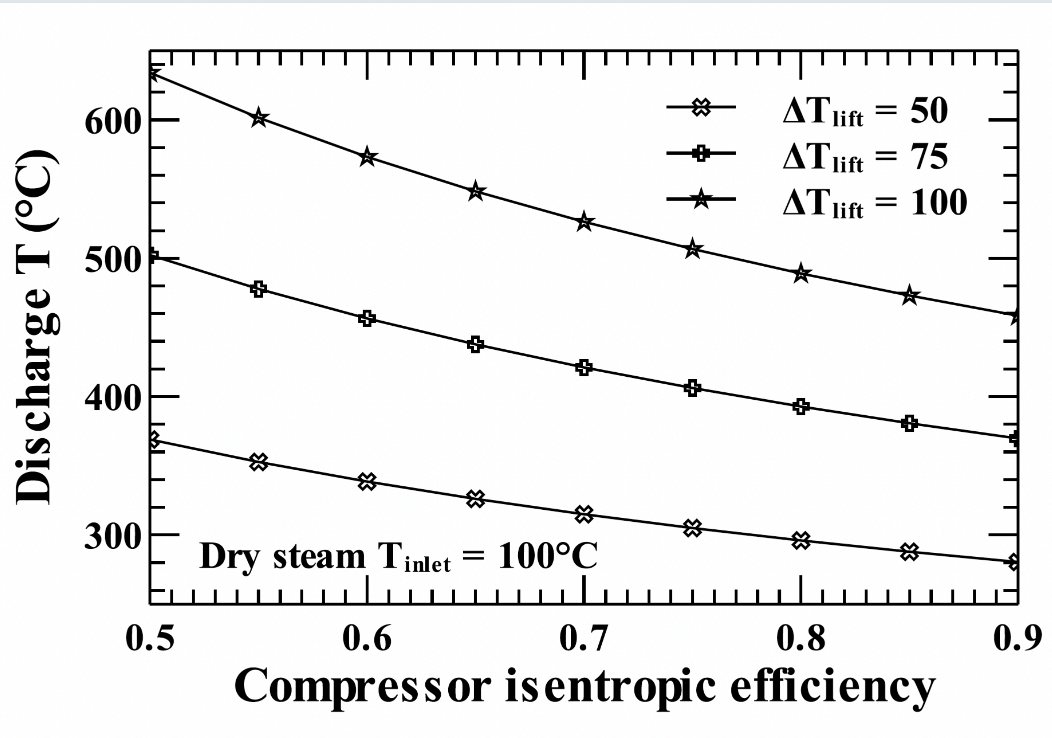

Figure 1. Dry steam discharge temperature at different rotary vane compressor isentropic efficiencies and temperature lifts

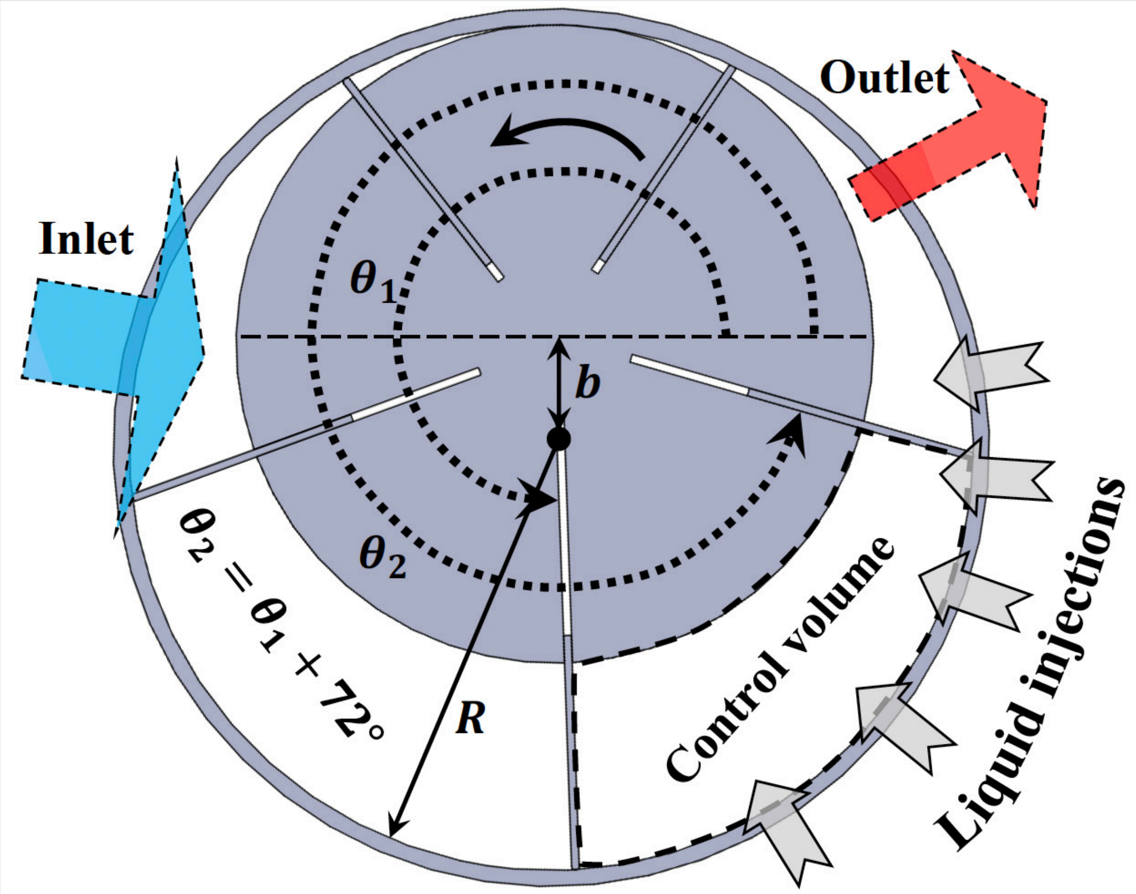

Figure 2. Liquid injections into a rotary vane compressor chamber. The inner cylinder is the rotor, the larger outer cylinder is the stator.

How hot steam can go during compression?

Due to mentioned properties, water is suitable to be selected as the refrigerant in the high stage of a high-temperature cascade heat pump system. Nonetheless, by assuming an initial temperature of 100°C, steam shows extremely high discharge temperature during the compression process in even relatively small temperature lifts. Figure 1 illustrates the discharge temperature of dry steam at different temperature lifts (from inlet temperature of 100°C). Even at a very high compressor isentropic efficiency of 0.9, the steam discharge temperature can easily pass 280°C, while the condensation temperature is just 150°C. The discharge temperature is 458.5°C for 200°C condensation temperature, corresponding to 15.6 bar discharge pressure. It should be noted that a more reasonable isentropic efficiency falls on 0.65, where the discharge temperature of dry steam will be 548.4°C for 200°C condensation temperature. Therefore, researchers have been actively seeking some ways to desuperheat the steam while keeping the same discharge pressure.

Liquid injection for desuperheating

Injecting liquid into compression process has been iterated recently to desuperheat the steam and bring it to the saturated state at compressor discharge [2, 3]. However, the theoretical framework of the compression with liquid injection should be investigated in detail as the presented thermodynamic models have assumed several oversimplifying assumptions, such as constant pressure and/or temperature during injection. These assumptions might not be valid as the expansion of the liquid inside the pressure chamber can decrease or increase the pressure/temperature of the mixture. The current thermodynamic approach attempts to provide solid insights for designers by having more realistic assumptions.

Figure 2 schematically illustrates a rotary vane compressor with several liquid injections. The control volume is also shown between two arbitrary vanes. It should be noted that the concept will remain almost the same for other compressor types. When the steam is compressed between two vanes, its temperature and pressure rise. The temperature of compressed steam is reduced via injecting liquid water.

Further, it has been shown that the rotary vane compressors can be useful for compressing two-phase liquid-gas mixture [4,5]. Therefore, the superheated steam can be basically prevented by compressing wet steam instead of dry steam. Figure 3 depicts the thermodynamic concepts of both dry and wet steam compression

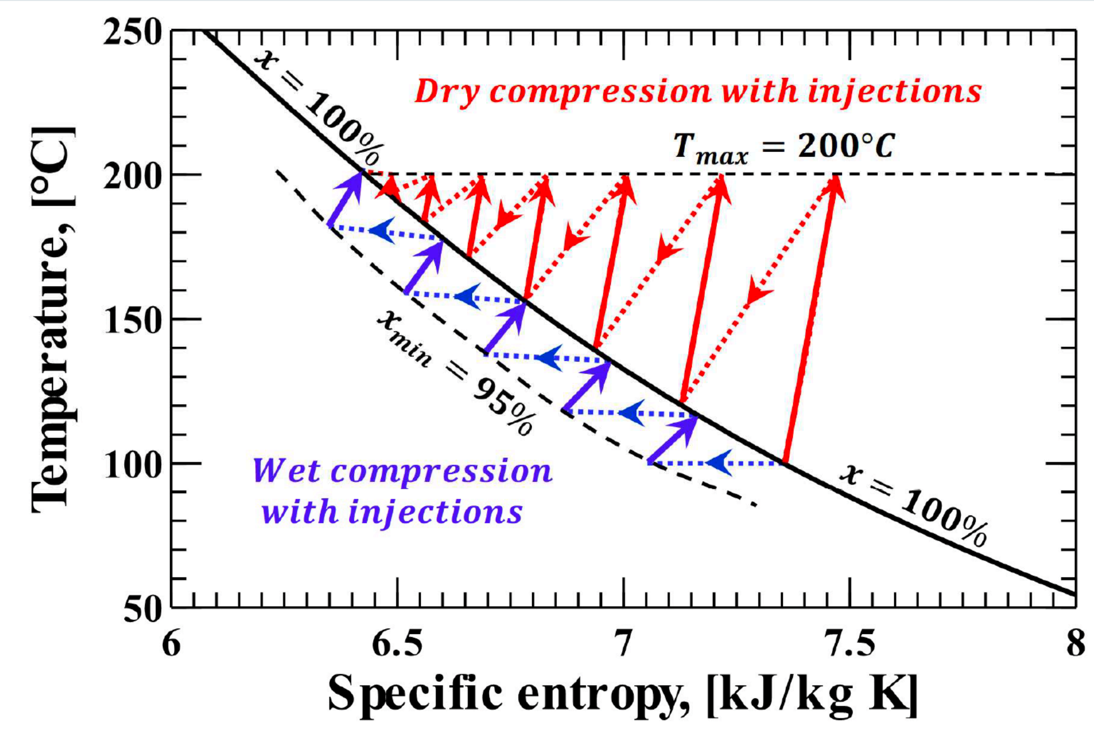

Figure 3. Dry and wet compression with injections for R718

with several injections in temperature-specific entropy diagram for water.

The red lines above the saturated vapor line (i.e., x = 100%) are called dry compression with injections, while the blue lines below the saturation line is named wet compression with injections. The solid lines are just compression, while the dotted lines are compression with injections for both concepts. Regarding the dry compression, the injections should be performed when the temperature of the compressed steam reaches a pre-set value (e.g., Tmax = 200°C). The injection brings the superheated steam to the saturation point. For the wet (aka two-phase) compression, the injection is performed during the compression to bring the wet steam quality to a predefined value (e.g., xmin = 95%), then the two-phase mixture is compressed to bring it to the saturated vapor state. The compressions with injections continue until the vapor reaches the desired discharge pressure.

Additionally, it has been observed that the injection process does not occur during a constant pressure or temperature, especially at higher temperature lifts; on the contrary, the pressure and temperature rises during injection (see Figure 3).

Compressor work and COP of the cycle

The compressor work is the summation of each compression step and the compression step during injections. The results show that the wet compression with injection requires 344.2 kW, and the dry compression with injection needs 405.82 kW. Moreover, the coefficient of performance (COP) is a good indicator to compare the effect of the dry and wet compressions with injections on the entire high-temperature heat pump system. In this study, it is assumed that the condenser outlet is a subcooled water with 2°C subcooling degree (i.e., 198°C). The COP is computed by dividing the delivered heat at condenser to the compressor work. COPs are extracted as 3.48 and 2.94 for wet and dry compressions with injections, respectively. Therefore, the wet or two-phase compression with liquid injections provides superior performance for the high-temperature heat pump system.

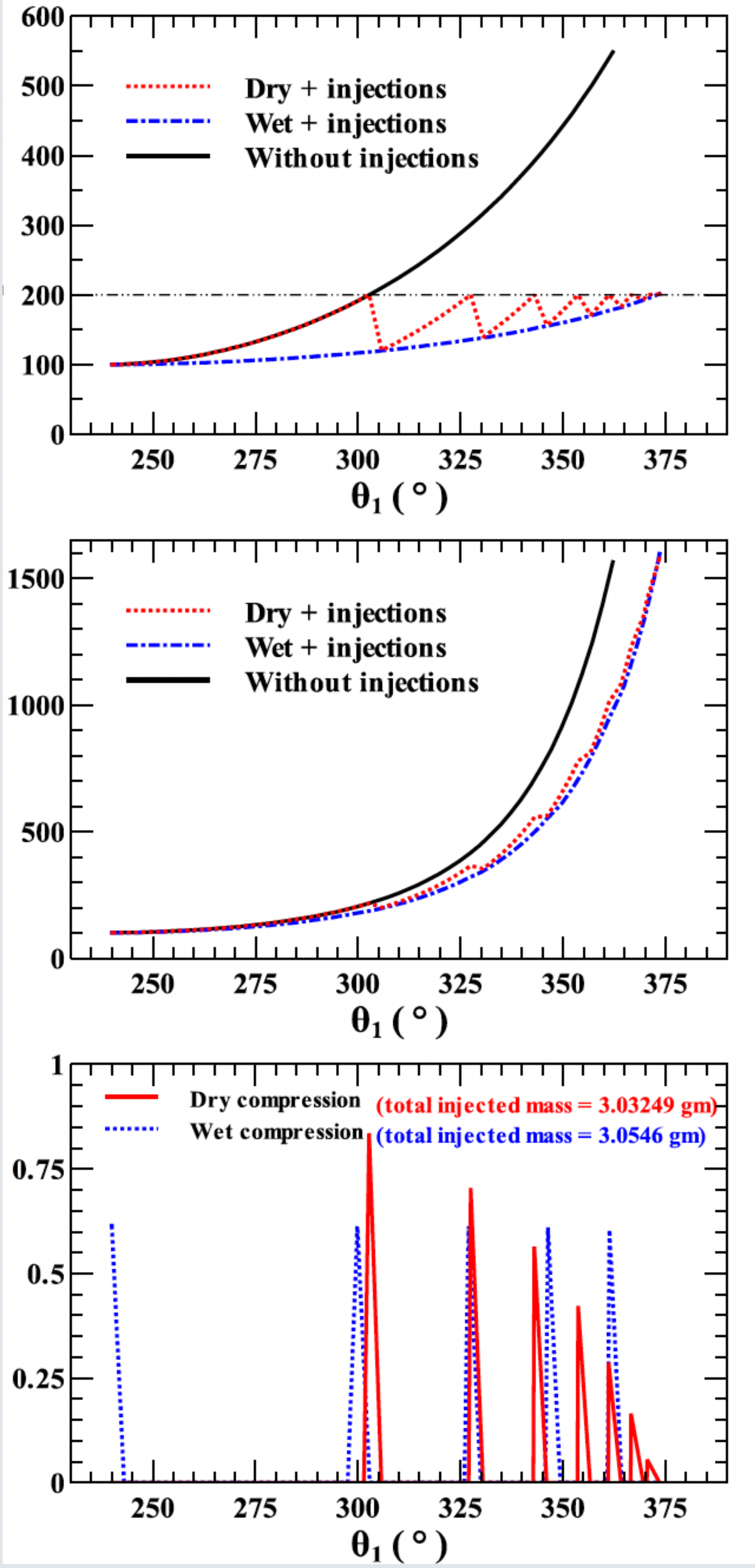

Figure 5. Temperature, pressure, and injected mass for wet and dry compressions with injections compared to the no injection case

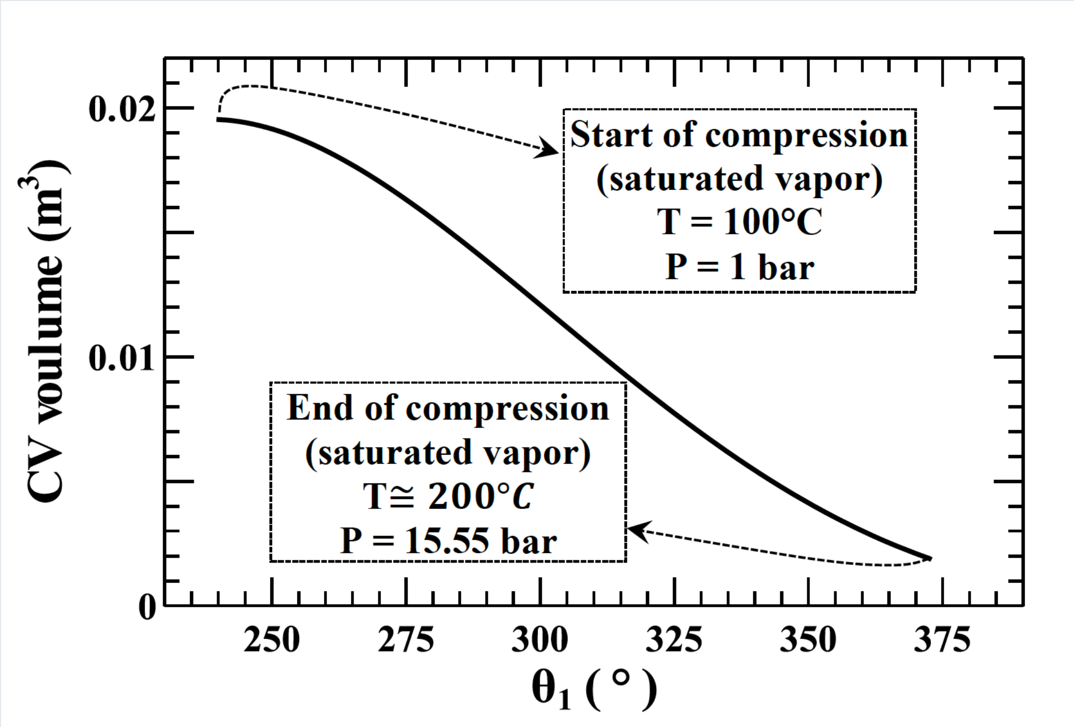

Figure 4. CV volume variations at different rotor angles

Conclusion

Desuperheating approach by injecting liquid into the compressor is an effective way that guarantees the desired temperature lifts at much lower compressor discharge temperature. The compression process can be performed under the saturated vapor line, wet compression with liquid injections, or above this line, dry compression with liquid injections. As an example, both approaches are analyzed through thermodynamic modeling of a rotary vane compressor. It is shown that the wet compression results in higher COP of the high-temperature heat pump. Detailed heat and mass transfer of the compression with injections can be simulated by a computational fluid dynamic tool in the next step. The obtained results can verify the validity of the considered assumptions in the presented thermodynamic analysis.

SEYED MOJTABA HOSSEINNIA
University of Sherbrooke
Canada
Seyed.Mojtaba.Hosseinnia@USherbrooke.ca
https://doi.org/10.23697/mxsx-0907