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Development and Validation of Multidimensional Models of Supercritical CO_2 Energy Conversion Systems for Nuclear Power Reactors

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ABSTRACT

Substantial potential benefits of using supercritical carbon dioxide (S-CO_2) as working fluid for energy transport in nuclear systems have already been identified [1]. They include, but are not limited to: high efficiency or energy conversion, compact turbomachinery, and the fact that CO_2 is widely available. However, several issues are yet to be resolved to make the S-CO_2 thermodynamic cycle a mature technology for application in future nuclear power plants.

The purpose of the proposed work is to develop, verify, and validate multidimensional mechanistic models of local flow and heat transfer in S-CO_2 and to demonstrate their application to selected components of S-CO_2 nuclear energy transport systems. Both steady-state and time-dependent operating conditions will be investigated. The new models will be applied to investigate the effect of physical properties variations of S-CO_2 at near-critical pressures on the operation and efficiency of compressors, design and thermal characteristics of heat exchangers, and dynamic characteristics and stability of closed-loop systems using S-CO_2 as the working fluid.

A typical supercritical CO_2 Brayton cycle with recompression is shown in Figure 1. The use of a recompressor, and the associated split of the recuperator into two separate heat exchangers, results in a reduced-heat rejection and higher system efficiency, compared to a single compressor-recuperator system. Also, the recompressing compressor helps to avoid pinchpoint problems in the recuperator. However, both compressors operate over the entire range of pressures, from near-critical to about 20 MPa, and the "cold" fluids in both recuperator units are at near-critical pressures.

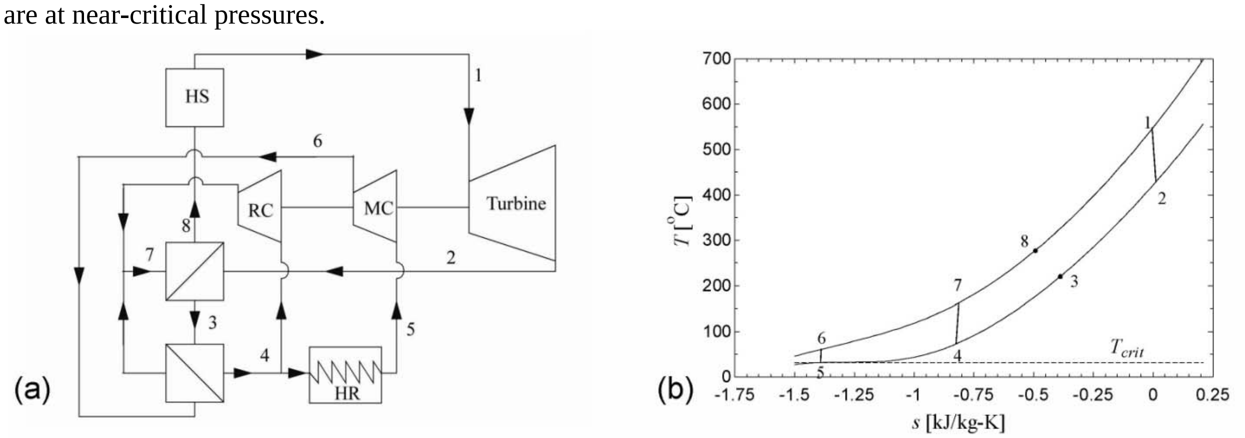

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Figure 1. Typical S-CO_2 nuclear power generation system with recompression: (a) system schematic, (b) T-s diagram. Notation: HS – heat source (S-CO_2 cooled reactor for a direct cycle system, or "liquid-metal"-to-"S-CO_2" heat exchanger), MC – main compressor, RC – recompressor, HR – heat rejection.

A very important issue for design optimization and performance analysis of future supercritical Brayton cycles is concerned with the effect of dramatic S-CO_2 property variations at pressures slightly above the critical pressure. The temperature-dependence of selected properties of S-CO_2 at a pressure corresponding to 1.1Pc is shown in Figure 2, compared to similar properties of water. It is interesting that the normalized properties of both fluids are very similar. So, developing appropriate methods of system analysis for one fluid should provide useful insight into the major characteristics of systems using the other fluid.

The objective of this project is to develop a mechanistic modeling framework to analyze the components of the supercritical Brayton cycle, the operation of which includes the near-critical pressure conditions of the working fluid, and of the impact of variable properties of S-CO_2 on the dynamics and stability of closed-loop systems. The proposed scope of work can be divided into three major parts, which are discussed next.

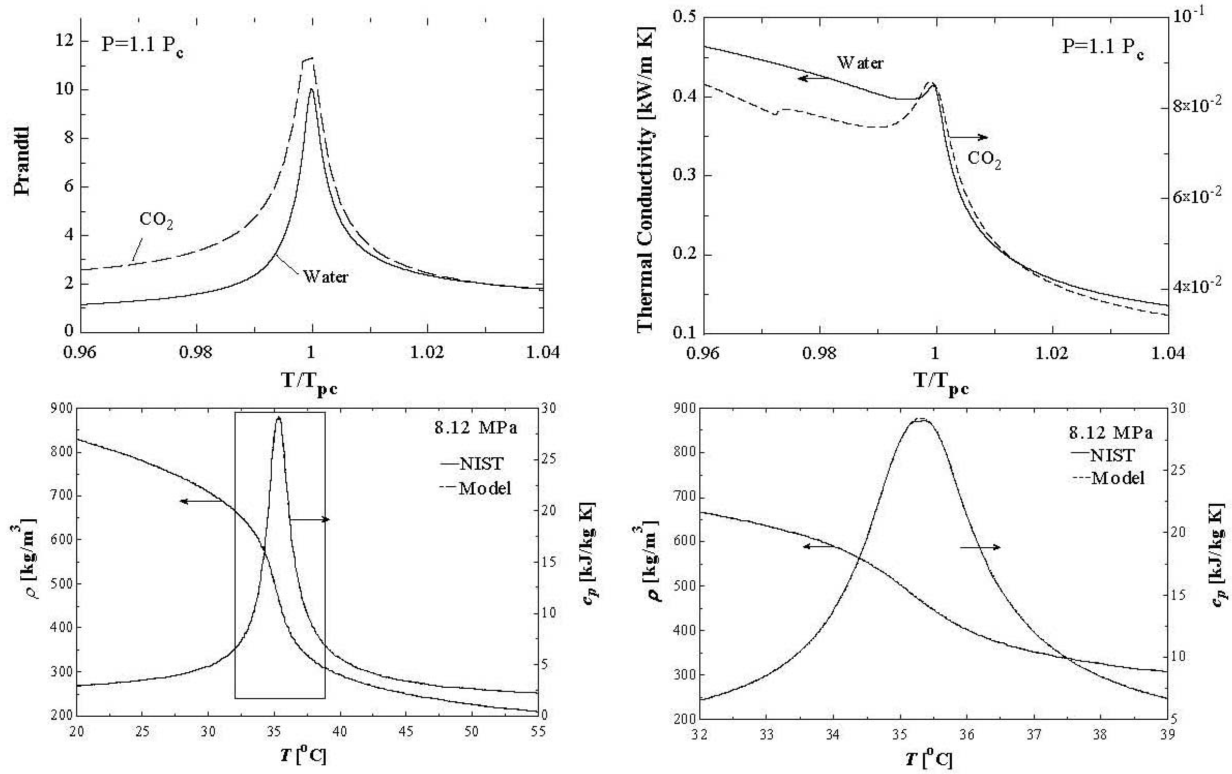

Figure 2. Physical properties of S-CO_2 and water at near-critical pressures. The lower plots show the NPHASE-CMFD-calculated density and specific heat for CO_2 compared against reference data [2].