MATLAB Implementation of a first-order compressor sizing tool

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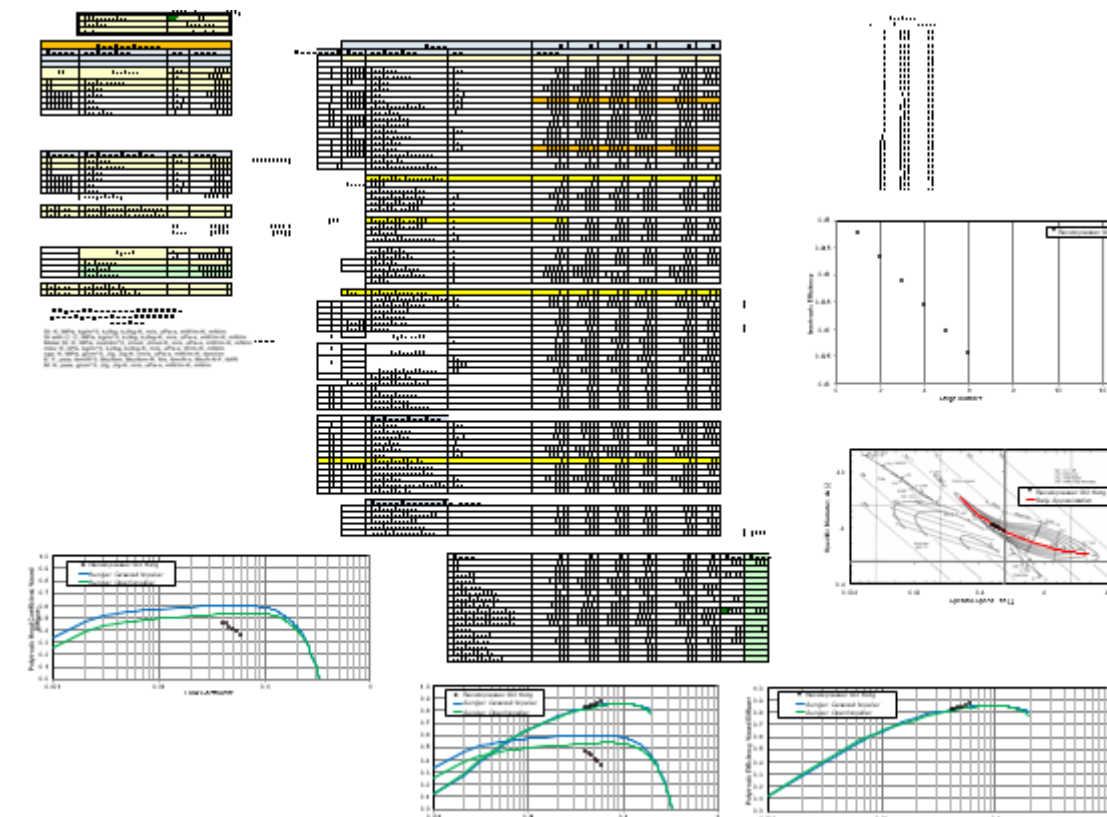## Introduction

As the host of the 2015 Supercritical Carbon Dioxide (sCO$_2$) Power Cycles Symposium, the possessor of the world's largest prototype sCO$_2$ turbine test loop, and the recent recipient of $13.1 million in sCO$_2$ research grants, Southwest Research Institute (SwRI) is an internationally-recognized leader in sCO$_2$ research.

Despite its prominence, SwRI lacks a systematic method to conduct parameter sweeps when optimizing first-order sCO$_2$ turbomachinery designs for clients, instead relying on a cumbersome spreadsheet program to compute single cases. The goal of this fellowship was to produce a command-line program capable of computing sCO$_2$ compressor dimensions and efficiencies for specified ranges of operating conditions and exporting the calculated data in a format useful for design decisions and later detail design work.

Due to computational challenges with operating conditions near the two-phase region, this program was not completed by the fellowship's end date. Instead, a MATLAB function was written to optimize compressor sizing at a single operating point. End users can conduct parameter sweeps by running this function within wrapper scripts as desired.

Supercritical CO$_2$ turbomachinery

Supercritical carbon dioxide is an attractive process fluid for turbomachinery power cycles due to its high density, high specific heat capacity and thermal conductivity, relatively benign chemical properties, and resource abundance. Brayton cycle efficiencies with sCO$_2$ are several points more efficient than steam Rankine cycles, and the high density of the working fluid allows sCO$_2$ turbomachinery to be an order of magnitude smaller, by length, than steam turbomachinery of comparable performance. However, coping with the high temperatures and pressures above the critical point is challenging at such small scales, and commercialization of sCO$_2$ technology is hindered by rotordynamic instability and manufacturing challenges, among other things.

This work addresses these issues by optimizing the dimensions of each stage in a multistage compressor to meet performance goals while maintaining constant tip and hub diameters, thus improving rotordynamic stability and easing manufacturing, assembly, and maintenance.
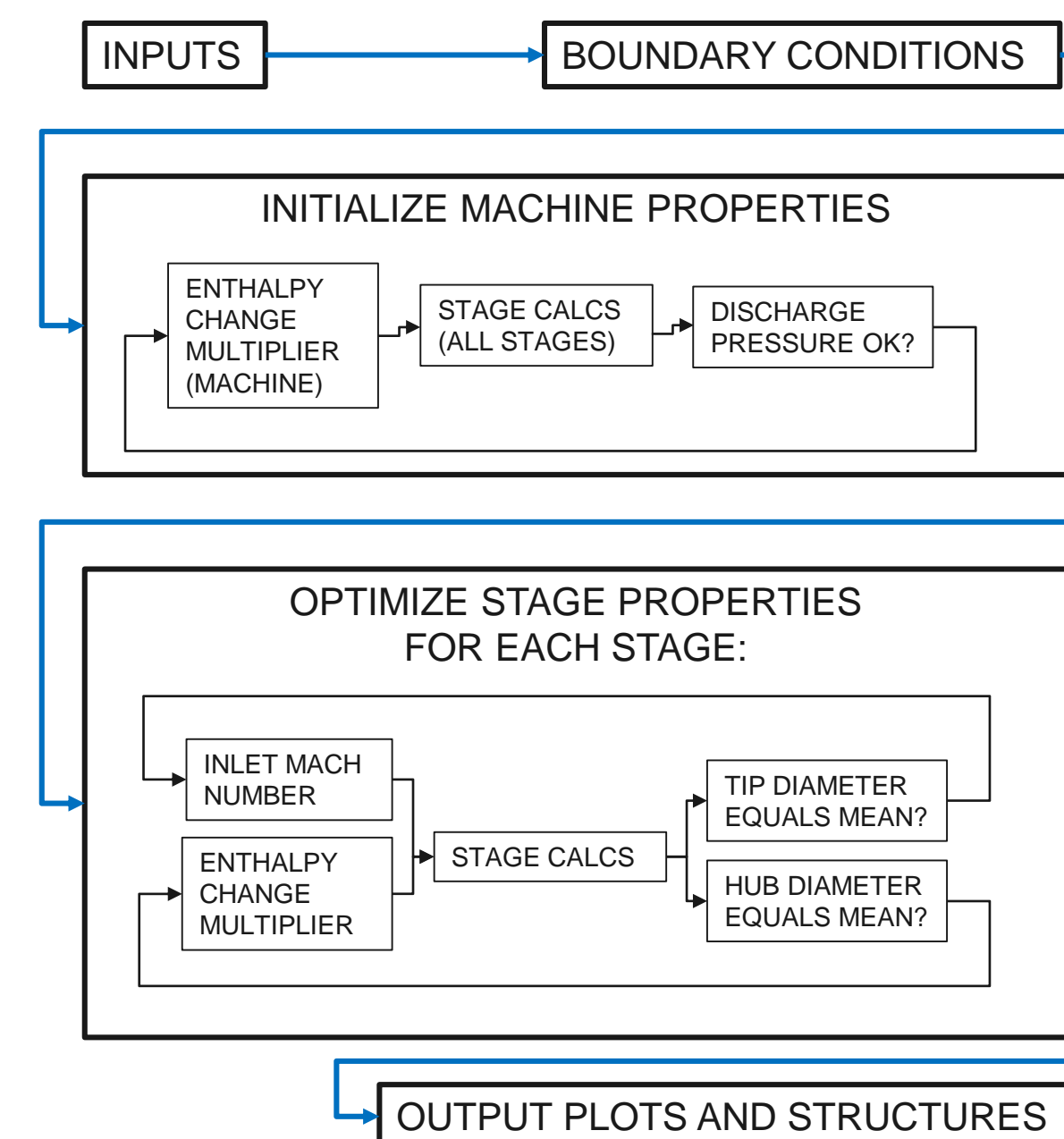
Pre-existing Excel design tool

SwRI engineers currently use this spreadsheet template to size new compressor designs. Operating conditions are entered in the blocks at left. Stage parameters are calculated in the columns of the main block and summarized in the bottom block. Users must manually add or delete columns for the desired stage count. The order of calculations is difficult to change, and the results cannot be easily exported to other engineering tools.

Graphical user interface

Once the initial MATLAB sizing package was working for all test cases, it was felt the complexity of the code called for a graphical user interface (GUI) to simplify management of inputs and outputs. The GUI was to allow users to create, edit, and save configuration files for compressors, operating cases, parameter sweeps, and output plots with a set of easily navigable menus. A user-selected combination of compressor, operating case, parameter sweep, and output plots was to be saved as an analysis file, and the resulting data were to be saved in a separate file. Regrettably, there was not enough time to write the complete GUI shell nor to integrate it with the command-line function.

MATLAB program structure

The optimization algorithm for stage properties is conceptually organized as depicted below.

Sample MATLAB outputs

The MATLAB function computes stage properties for a single machine definition (stage count and running speed) and set of operating conditions (mass flow rate and suction and discharge operating pressures and temperatures). All information for each stage is saved to a separate data structure; stage data structures and other machine information is saved to a single structure for the machine. A wide range of plots, including the plots below, is saved to a user-specified folder, allowing the user to graphically examine stage properties and convergence rates.
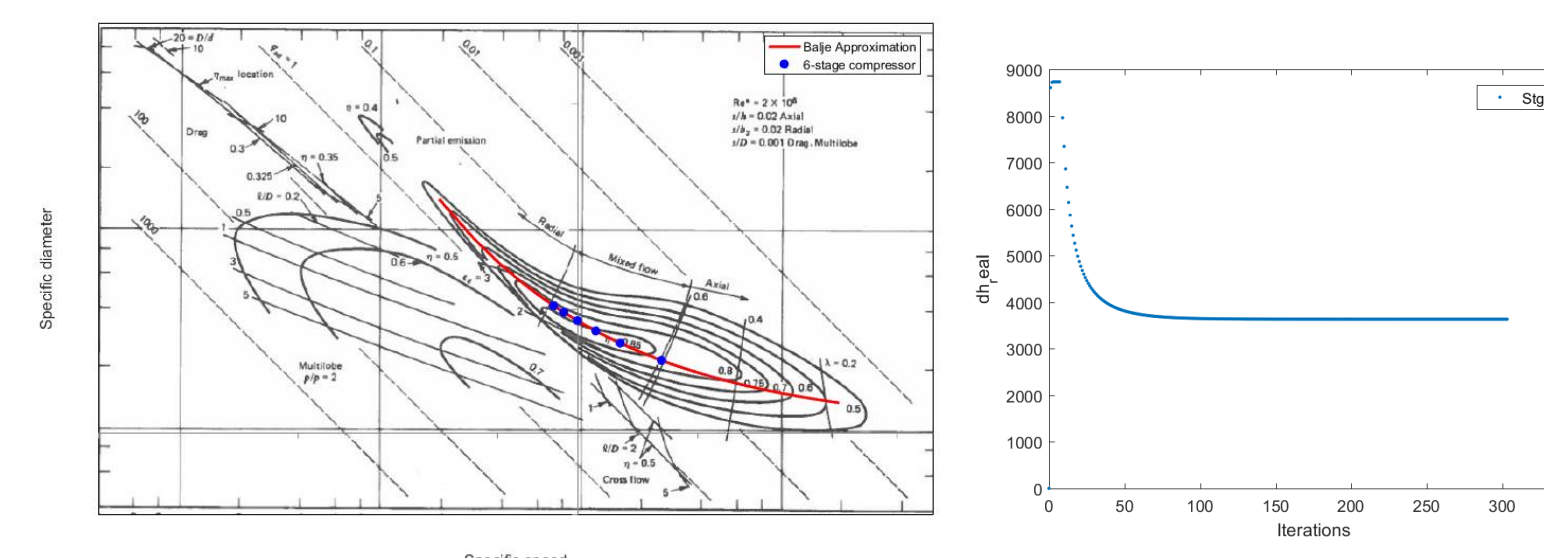
LEFT: Specific speed and diameter for each of six stages of a compressor, overlaid on a plot from *Turbomachines: a guide to design, selection, and theory*, by O.E. Balje (Wiley, 1981).

RIGHT: Convergence of the computed enthalpy change for stage 1 of the same compressor.

Further work

Further work should focus on developing a robust calculation algorithm that avoids the two-phase region and other divergence errors, perhaps by a path-finding routine that explores all possible calculation sequences before returning an error. Due to the wide variety of operating conditions which may be expected to occur in production sCO$_2$ turbomachinery and the different ways the optimization loop may respond to these, it is probable that no single calculation sequence exists which will return results for all physically reasonable combinations of operating condition and stage count.

Besides an adaptive algorithm, the code lacks the originally requested parameter sweep capability. End users may easily write MATLAB scripts to run the single-condition code for any desired range of parameters and process the saved data from each run as needed, but the first-order sizing tool would be more complete and user-friendly if this capability was native to the app package.

Although the sizing tool is meant for use from the command line, a finished GUI would encourage use by engineers who are less comfortable with command-line computing.
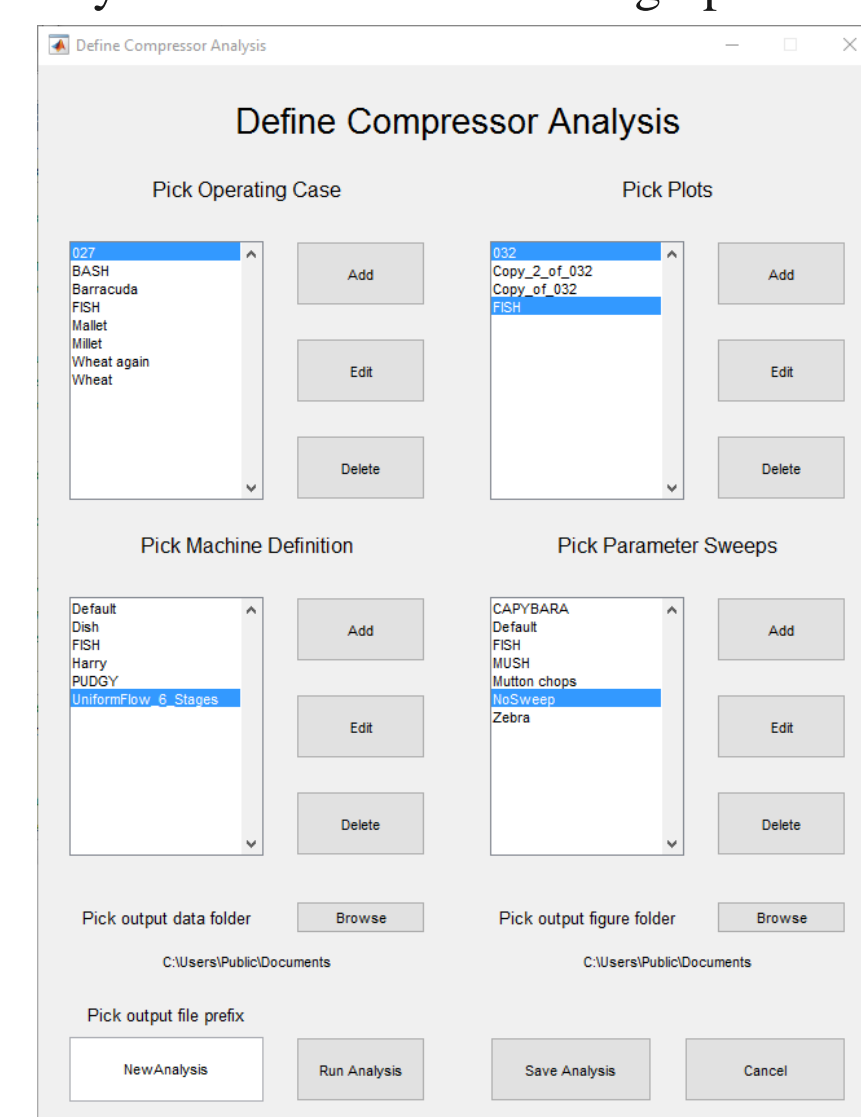
Acknowledgments

Further information

For a comprehensive introduction to supercritical carbon dioxide power cycles, the current state of the art, and related work at SwRI, see the proceedings of the International Symposia on Supercritical CO$_2$ Power Cycles.