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A MATLAB Toolkit to Generate and Visualize Thermodynamic Property Data in Undergraduate Thermodynamics Courses

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In many undergraduate engineering thermodynamics courses, applications of the 1st and 2nd laws of thermodynamics involve solid-liquid-vapor phase diagrams of water and refrigerants such as R134a, as well as thermodynamic properties of states spanning different phases. Virtually all exercises require strenuous efforts of looking up data of specific volume (v), specific internal energy (u), specific enthalpy (h) and specific entropy (s) using the property tables in textbooks presenting these properties as a function of pressure (p) and temperature (T) followed by tedious linear interpolation for state properties that do not have exact entries in these tables. In most US institutes, it is quite common that extra efforts are required from the instructors to explain the manual extraction of useful information from these tables. Depending on the known properties and material behavior some of the property determinations may require several steps. Although this multistep process including decision making and calculations is an important engineering skill to learn, such efforts are always time consuming, and oftentimes eclipses important and basic concept of thermodynamics. When too many properties and too many associated interpolations are involved, process becomes repetitive, prone to errors, and boring. It will be helpful to both the instructors and students to visualize specific thermodynamic processes in the standard 3-D p-v-T charts, as well as u, h and s dimensions, before proceeding to more advanced concepts. A user-friendly interface is necessary to promote learning in the 21st century especially for the younger generation growing up in a digital age.

Mathworks supported us with a micro-grant to build a Matlab toolkit aiming to replace the tables by digital input/output, to allow 3-D visualization, to perform calculations in rudimentary thermodynamic processes (*e.g.*, isobaric, isothermal, and isentropic) for water, R134a and other refrigerants. The project began in Jan 2021 and concluded in Dec 2022, supporting participations of several undergrad/graduate students and class evaluation.

This Toolkit is essentially a desktop calculator app with convenient programming features with a goal of replacing the interpolation that students generally do in standard thermodynamics courses in mechanical, chemical and biomedical engineering. The tabulated discrete data in the textbook and/or published by NIST are converted into a database, and the intermediate values are computed by built-in linear interpolation consistent with textbook data and solutions. It can generate 2-D plots (*e.g.,* p-v, T-v, T-s) and 3-D plots (p-v-T) with the flexibility of 3D rotations indicating thermodynamic states and process lines. For instance, water going from cold liquid to hot steam under constant pressure that involves phase change and latent heat of vaporization can be visualized in all of these graphs.

Figure 1 depicts the method used to define a state in the Toolkit, which requires a unique state label, and any two independent thermodynamic properties of a chosen substance among temperature, pressure, specific volume, specific internal energy, specific enthalpy, specific entropy, and vapor quality (x). Value of each property can be specified in a unit that can be selected from a predetermined list.

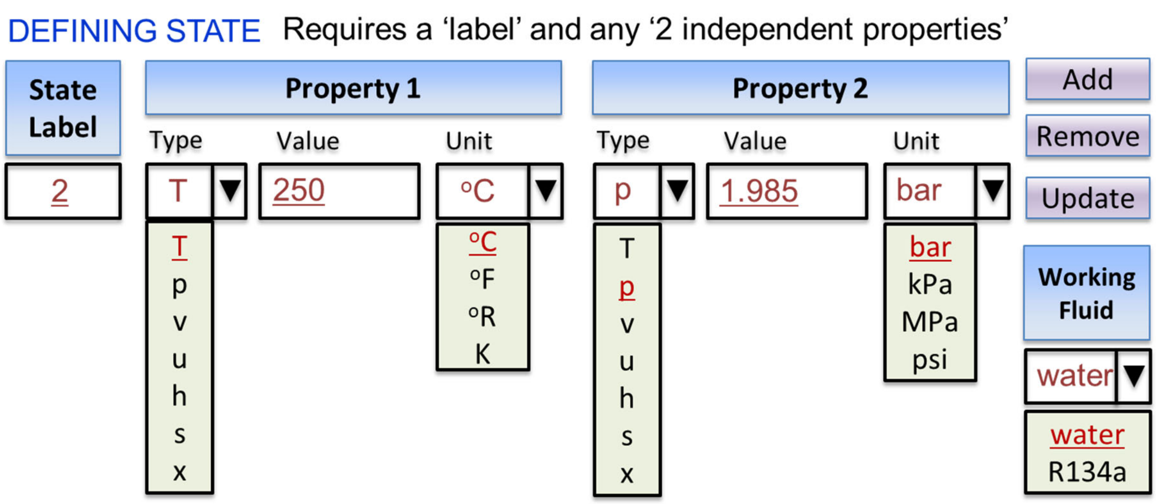

Figure 1: Entering information for a state in the Toolkit. Each state requires a unique label, two independent properties. Type and unit of any property can be selected from a pulldown list depicted by boxes underneath the entry fields. In this example, water at 250ºC temperature and 1.985 bar pressure is defined and labeled as state 2. User entries are underlined for clarity.

a) List of States

State Label	Fluid	Phase	P [bar]	T [°C]	v [m^3/kg]	u [kJ/kg]	h [kJ/kg]	s [kJ/kgK]	x
a	Water	Subcooled liquid	1	20	0.0010	83.9500	83.9600	0.2966	N/A
b	Water	Superheated vapor	1	150	1.9363	2.5827e+03	2.7763e+03	7.6115	N/A
c	Water	Subcooled liquid	5	150	0.0011	631.6800	632.2000	1.8418	N/A
d	Water	Saturated Vapor	5	151.9000	0.3749	2.5612e+03	2.7487e+03	6.8212	1
1	R134a	L-V mix	5	15.7400	0.0209	153.2850	163.7000	0.5920	0.5000
2	R134a	L-V mix	1	-26.4300	0.1156	134.0613	145.6171	0.5920	0.6014

b) List of Processes

Process Label	Start State	Final State	Process Type
b-c	b	c	Isothermal
c-d	c	d	Isobaric
a-b	a	b	Isobaric

c) List of processes to be shown on the diagrams

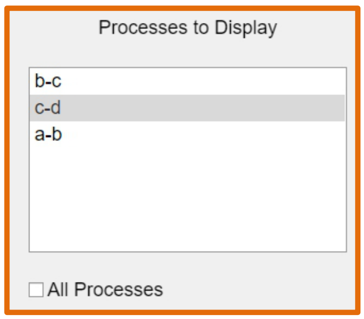

Figure 2: A snapshots of the tables stored in the Toolkit. a) List of defined states and their properties. b) List of defined processes that can take place among the defined states. c) List of processes to display on the diagrams can be used to turn on or turn off any process line on the diagrams. T-s diagram in Figure 3 has only process c-d line drawn based on this list.

Once information about a state is entered all the other thermodynamic properties of that state are determined from the database in the Toolkit. Then all state properties are entered into an internal table, which is visible to the user, for further use. A snapshot of the table from the Toolkit is provided in Figure 2a. Once the states are defined, optionally, processes between these states can also be defined and stored in a separate table in the Toolkit (Figure 2b) for further use. A separate list exists in the UI (Figure 2c) to mark which process lines should be drawn in process diagrams provided by the Toolkit. User may select, all, none, or any combination of defined processes in this list.

The Toolkit can produce 2-D diagrams like p-v, T-v, T-s, and 3-D diagram (p-v-T) showing all the defined states and processes. Figure 3 shows a sample T-s diagram produced by the Toolkit indicating all 4 states listed in Figure 2a, process line for process c-d as listed in figure 2c, as well as a set of isobars, isotherms, constant volume, and constant entropy lines, selected by the user in a separate table in the Toolbox. Figure 4 has a snapshot from the Toolkit illustrating how isolines shown in Figure 3 are specified.

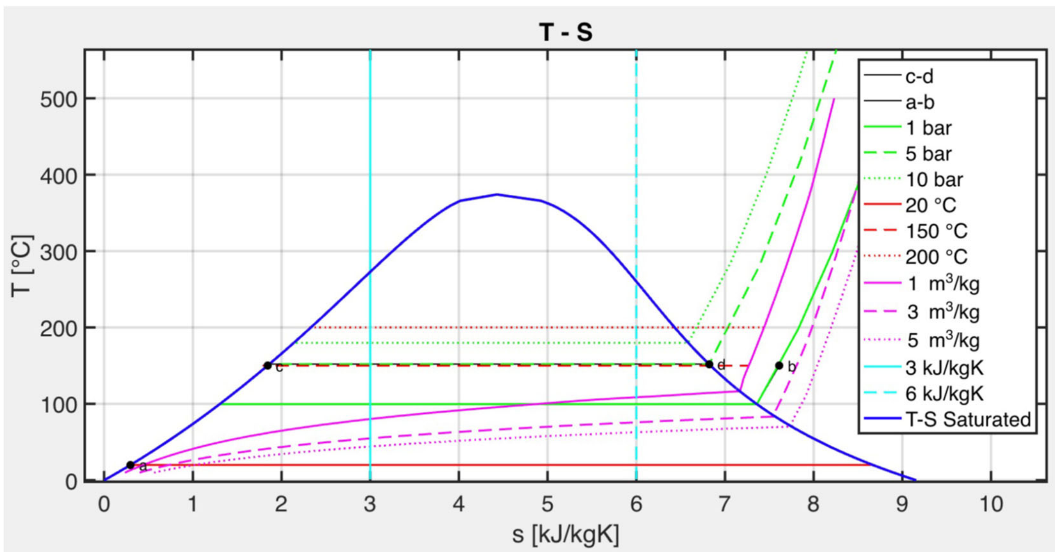

Figure 3. Snapshot of a sample T-s diagram from the Toolkit indicating 4 states in Figure 2a. A set of user selected isobars (1 bar, 5 bar, and 10 bar), isotherms (20ºC, 150ºC, and 200ºC), isovolumetric lines (1 m^3/kg, 3 m^3/kg, and 5 m^3/kg), and isentropic lines (3 kJ/kg·K and 6 kJ/kg·K) are also shown on the diagram.

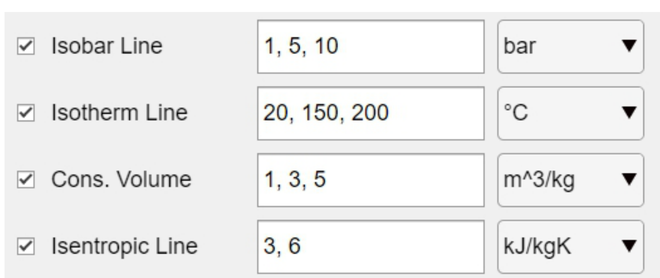

Figure 4. A snapshot of UI used to specify which isolines should be shown on the diagrams. Units of each variable can be changed from a pulldown menu similar to the property entry shown in Figure 1. Checkboxes are used to activate/deactivate specific isolines on the diagrams.

A graduate student, Mir Masoud Ale Ali, supported by the MathWorks grant spent about 6 months to build the preliminary toolkit framework such that numerical value of the thermodynamic quantities can be read from the standard tables. An undergraduate student, Bjorn Kierulf, played a major role in developing the MATLAB codes, converting thermodynamic data from National Institute of Standards and Technology (NIST), and constructing the graphics interface to display 3D states of water and thermodynamic processes (*e.g.*, isothermal, isobaric and isochoric). A second graduate student, Tingting Zhu, then took over the project and involved in debugging, implementing flexibility in 3D graphics, and adding data of refrigerant R134a making the toolkit possible to be extended to other refrigerants if data are available from NIST or other reliable sources. The PI faculty meet with the students every 1-2 weeks to ensure alignment of progress with the project goal and objectives.

The toolkit was largely finished in December 2022, though a few loose ends remain. A few ME 2380 Thermodynamics students in Spring 2023 will conduct alpha testing and to identify potential bugs. The toolkit should be ready to be given to Summer I classes (May-June 2023) for their homework. It is noted that finding data from standard tables will still be taught in class because MATLAB is not accessible during midterm tests or final exam. Special arrangement is necessary for the assessment exam to be held in computer labs. Survey will be conducted to check level of satisfactory and competency of the toolkit for statistical analysis and further improvement. Graduate teaching assistants (GTA) and other course instructors (roughly 6-7) who are apt in MATLAB will be invited for training for 1-2 hours. The full implementation is expected to be in Fall 2023, when 3 concurrent sections with 2-3 instructors and 3-4 GTA will be involved. Course evaluation by students, instructors and GTA will be conducted by semester end (Dec 2023).

Should the toolkit prove to be successful, we will invite other course instructors from other departments, namely, chemical engineering, bioengineering, physics, chemistry, and energy (graduate program) at Northeastern University to short training sessions. The feedback will further promote and implement the toolkit. We are current communicating with MathWorks to explore the possibility of installing the toolkit online to reach wider community around the nation and beyond. We also approach publishers to see whether the toolkit can be incorporated into standard textbook.