Modeling Two-phase Flow and Vapor Cycles Using the Generalized Fluid System Simulation Program

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This work presents three new applications for the general purpose fluid network solver code GFSSP developed at NASA's Marshall Space Flight Center: (1) cooling tower, (2) vapor-compression refrigeration system, and (3) vapor-expansion power generation system. These systems are widely used across engineering disciplines in a variety of energy systems, and these models expand the capabilities and the use of GFSSP to include fluids and features that are not part of its present set of provided examples. GFSSP provides pressure, temperature, and species concentrations at designated locations, or nodes, within a fluid network based on a finite volume formulation of thermodynamics and conservation laws. This paper describes the theoretical basis for the construction of the models, their implementation in the current GFSSP modeling system, and a brief evaluation of the usefulness of the model results, as well as their applicability toward a broader spectrum of analytical problems in both university teaching and engineering research.

Nomenclature

A	Area
C_{min}	Capacity rate of minimum capacity fluid
C_r	Fluid capacity ratio (or capacity rate ratio)
C_s	Slope of enthalpy of saturated air v. temperature
c_p	Specific heat at constant pressure (per unit mass)
$GFSSP$	Generalized Fluid System Simulation Program
h	Enthalpy (per unit mass)
HEX	Heat Exchanger
K_m	Mass transfer coefficient for cooling tower
$\dot{m}$	Mass flow rate
NTU	Number of transfer units
Q, q	Heat transfer, heat transfer per unit mass
$\dot{Q}$	Rate of heat transfer
P	Pressure
T	Temperature (dry bulb unless otherwise noted)
TC	Characteristic cooling tower coefficient
$\dot{V}$	Volumetric flow rate
v	Specific volume
$VTASC$	Visual Thermofluid Analyzer for Systems and Components
w	Work transfer per unit mass
δ	Correction factor for enthalpy of saturated air v. temperature
ϵ	Effectiveness

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ω	Humidity ratio

Subscripts

a	Air
act	Actual
ave	Average
in	Inlet conditions
out	Outlet conditions
sat	Saturation conditions
w	Water
wb	Wet bulb

Superscript

$+$	Adjusted capacity rate for water in a cooling tower including both water- and air-side properties

I. Introduction

This project expands the capabilities of NASA's GFSSP software, developed at Marshall Space Flight Center, to include (1) a two-phase flow problem, including psychrometric calculations and two-phase flow, for design and sizing cooling towers, in heating, ventilation, air-conditioning, & refrigeration applications as well as for thermoelectric power plant cooling; (2) a work-consuming vapor cycle, the vapor-compression refrigeration cycle, with applications in air-conditioning and process cooling; and (3) a work-producing vapor cycle, the Rankine cycle, with applications in thermoelectric steam power generation as well as Organic Rankine Cycle systems. These systems are widely used across engineering disciplines in a variety of energy systems,and these models expand the capabilities and the use of GFSSP to include fluids and features that are not part of its present set of provided examples. Section II describes the development of Model (1), Section III describes the development of Models (2) and (3), and Section IV discusses the general applicability of GFSSP toward a broader spectrum of analytical problems, followed by Section V which discusses future plans for university teaching and engineering research inspired by these new models.

I.A. Generalized Fluid System Simulation Program

The Generalized Fluid System Simulation Program (GFSSP) was conceived by the second author in the 1990s and awarded NASA's Software of the Year designation in 2001.[1] It is a fluid-thermal systems network analysis code written in Fortran which may be compiled directly or accessed through the visual thermofluid dynamic analyzer for systems and components (VTASC) graphical user interface. The model outputs provide pressure, temperature and species concentrations for fluids in complex systems, either at steady state or as a time series for transient analysis.[2] It is a finite volume code that represents fluid networks as a connected series of nodes and branches. The work that follows was performed with GFSSP Version 7.

An Educational version of GFSSP is available at no charge to U.S. institutions through an application to Marshall Space Flight Center (MSFC) from a university representative. GFSSP was developed at NASA to analyze aerospace industry problems by members of the Propulsion Systems Department at MSFC, and its core user group consists of NASA employees and contractors. However, its property packages cover a number of fluids commonly used in a variety of engineering systems, and the generalized and flexible nature of the modeling system lend themselves to a number of engineering problems involving complex thermal-fluid networks. This work provides a new set of models built on the GFSSP framework to demonstrate its capabilities in three classical engineering energy systems. The first, a cooling tower performance model, was developed primarily by the first author and will be used for teaching thermodynamics to mechanical engineering students and in sustainability research at the water-energy nexus. The second, a vapor-compression refrigeration system model, and third, Rankine power cycle models were developed primarily by aerospace engineering student C. Ursachi.

II. Two-Phase Flow

II.A. Application: Cooling Tower

Performance modeling of cooling towers is a multiphysics problem involving simultaneous heat and mass transfer, two-phase flow, and psychrometric treatment of atmospheric air. Its applicability extends from small, constant-area cooling towers used for providing chilled water to buildings to large, parabolic cooling towers providing chilled water to the condensers of thermoelectric power plants. Predicting the performance of these devices involves a number of physical process and a great deal of uncertainty.

The earliest mathematical models of cooling towers were developed by Merkel in the 1920s.[3] By assuming that the flow rate of water leaving the tower (due to evaporation or drift) was negligible, and ignoring the computation of the exact state of the air leaving the tower, he was able to avoid the necessity of obtaining detailed detailed data about fill performance and mass transfer coefficients within the tower by treating it as a lumped system with an empirical "Merkel number".[4] Assumptions limiting to the accuracy of the model include: Lewis number of 1 (simplifying the relationship between heat and mass transfer), air exiting the tower is saturated with water (an "ideal" cooling tower in terms of mass transfer), and the aforementioned neglect of water losses (lack of adherence to mass conservation for water).[4]

An important improvement for mechanical engineers surfaced in the 1980s, when the effectiveness-number of transfer units (ϵ-NTU) method, commonly used for heat exchanger (HEX) analysis was adopted for cooling towers.[5–7] The main difficulty in this adaptation was the fact that mass transfer from the water stream to the air stream (that is, *latent* heat transfer from the air stream), since the ϵ-NTU model relies on temperature differences to describe the potential and actual heat transfer from one fluid stream to another. Braun[6] details the impacts of neglecting water losses, usually 1-4% of the total water mass flow rate, and fits his version of the ϵ-NTU model to experimental data, alongside prior models.

The model presented here is based on the ϵ-NTU formulation presented by Jaber and Webb[7] in 1989. The description of the model that follows, and the flowcharts presented in figures and are developed for a single control volume; however, the GFSSP implementation described in can be divided into any desired number of segments. Dividing the model into 2 or more increments will increase accuracy; however, a sensitivity analysis on small-scale cooling towers indicates that dividing the cooling tower into more than 6 segments is unlikely to yield significant returns in accuracy (see Ibid.,[7] Figs. 5–8).

The model of Jaber and Webb[7] has the advantage of conforming precisely to the conventional effectiveness-NTU method of heat exchanger analysis familiar from any basic undergraduate engineering heat transfer course. Because it is traditionally applied where both fluids are in a single phase, the actual and maximum heat transfer possible must be carefully defined. An "air-side effectiveness" was proposed by Braun et al:[6]

$$\frac{Q_{act}}{Q_{max}} = \frac{\texttt{Actual heat transfer from the water stream*}}{\texttt{Heat transfer IF the exiting air were saturated at water inlet temperature}}$$

Jaber and Webb then showed that it was possible to provide a generalized effectiveness which is based on the minimum capacity fluid,[7] as in classical ϵ-NTU HEX analysis:

$$\frac{Q_{act}}{Q_{max}} = \frac{\dot{m}_w c_{p,w}(T_{w,in} - T_{w,out})*}{C_{min}(h_{a,sat@Tw,in} - \delta - h_{a,in})}$$

where δ is a correction factor that helps to account for the non-linearity of enthalpy of saturated air as a function of temperature.[7]

* The numerators of both equations above, representing the heat rejected by the water, are also equal to the heat received by the air stream if the tower is adiabatic (negligible heat transfer through the walls).

II.A.1. Model for Counterflow Sizing Calculation

Given experimental data relating the mass flow rates of air and water, the state of the incoming air, and the temperature of the water entering and exiting the control volume, a mass transfer coefficient K_m that is characteristic of that cooling tower may be obtained.

The steps are illustrated in Figure 1 and are derived from the presentation of Jaber and Webb.[7] Numbers within the flowchart correspond with equations in the referenced document. This was deemed "Counterflow Sizing Calculation" procedure[7] as it determines the NTU value, and thus the 'size' of the tower.

First, the slope of the curve of the enthalpy of saturated air versus temperature is obtained for the range of water temperatures applicable. Next, a water "capacity rate" is calculated which captures the water's potential to release heat to the air. As in any ϵ-NTU analysis, the minimum capacity fluid must be determined to obtain the proper denominator.

The numerator is calculated in a straightforward manner, using a constant specific heat for water over the range of temperatures applicable (an assumption which introduces little to no error).

The correction factor is calculated to improve the accuracy of the denominator (Q_{max}):

$$\delta = \frac{h_{a,sat@Tw,in} + h_{a,sat@Tw,out} - 2h_{a,sat@Tw,ave}}{4}$$

The effectiveness and number of transfer units are calculated as for any HEX ϵ-NTU analysis.

The number of transfer units here, however, has a significant physical meaning in the context of the cooling tower. It represents a mass transfer coefficient (per unit area), multiplied by the tower area, divided by the minimum of the air capacity rate, $\dot{m}_a$, and the water capacity rate, $\dot{m}_w^+ = \frac{\dot{m}_w c_{p,w}}{C_s}$.

The characteristic coefficient of the tower, TC, is provided in relation to the actual mass flow rate of water because the cooling of the water is the ultimate purpose of the device. This tower coefficient may now be used to predict performance for the same tower under other conditions, as described in the following section.

II.A.2. Iterative Model for Counterflow Rating Calculation

Given knowledge of the mass transfer coefficient K_m, or the lumped term $K_m A$ that is characteristic of a given cooling tower, a predictive model may be used to model its expected cooling performance.

The steps are illustrated in Figure 2 and are again derived from the presentation of Jaber and Webb.[7] Numbers within the flowchart correspond with equations in the referenced document. This was deemed "Counterflow Rating Calculation" procedure[7] as it determines the exiting water temperature, and thus the 'rating' of the tower given its characteristic coefficient.

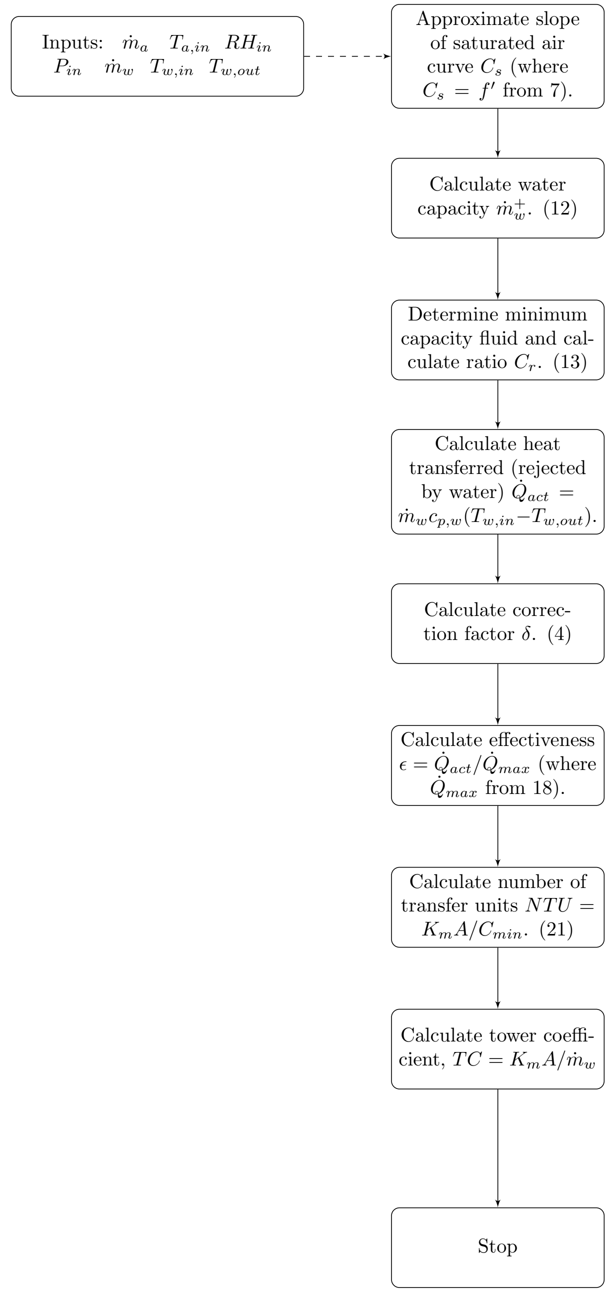

Figure 1. Procedure for calculating tower characteristic coefficient, $K_m A$, given performance data for a specific cooling tower.

Note that a cooling tower 'rating' is commonly used in industry to refer to its performance under a defined set of testing conditions, defined as $\dot{V}_w = 3\frac{gal}{min}$, $T_{w,in} = 95F$, $T_{w,out} = 95F$, and $T_{wb,in} = 78F$ for a "nominal ton" of cooling.[8]

II.A.3. Iterative Model for Counterflow Operational Setting or Fan Selection

An additional model was created for the benefit of practicing engineers who may have the opportunity to select the operational method or fan for an existing forced-draft counterflow cooling tower. Its calculation procedure is an adaptation of both Figure 1 and Figure 2 in which the user provides a desired water outlet temperature, and the necessary air flow rate given the tower's characteristic coefficient.

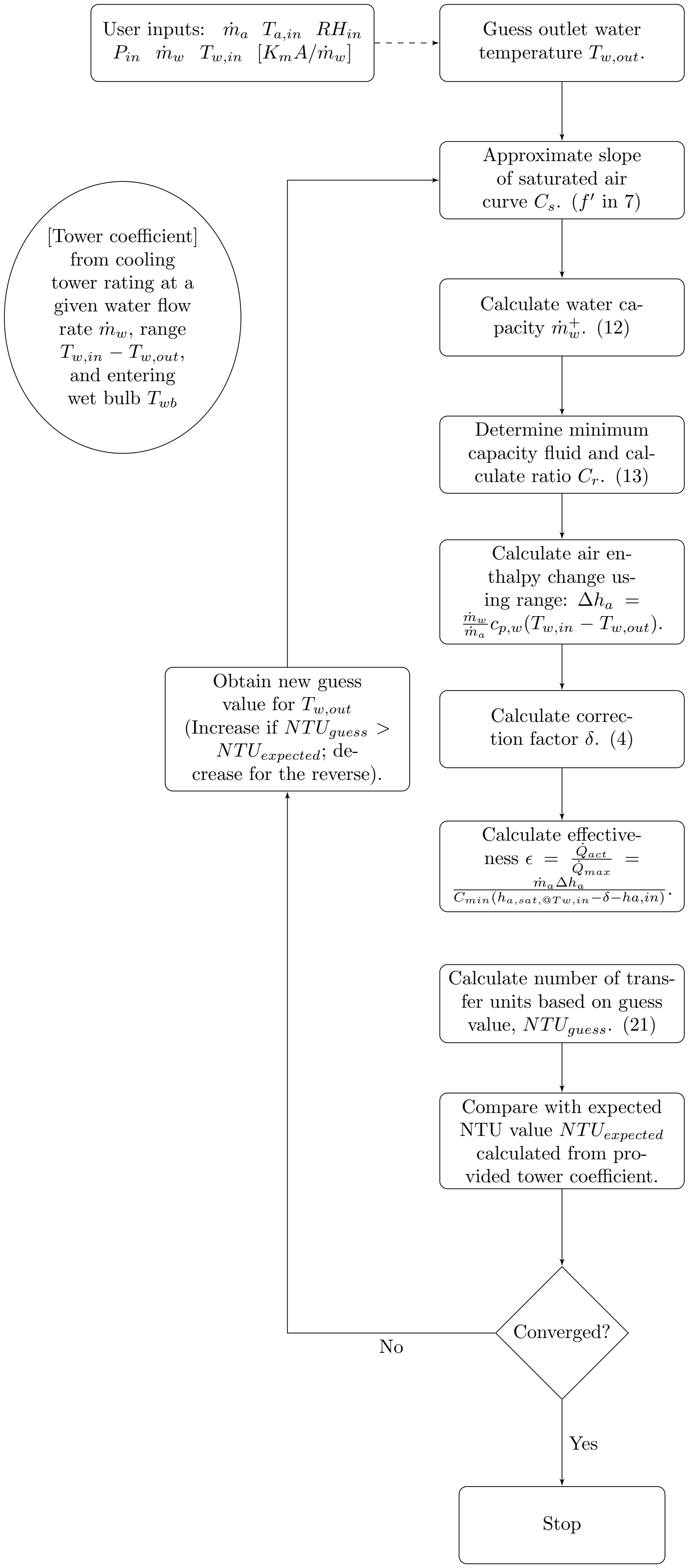

Figure 2. Procedure for calculating tower performance, given $K_m A$ for a specific cooling tower derived from performance data.

II.A.4. *Verification and Validation*

For the models described in Sections II.A.1, II.A.2, and II.A.3, verification of the Matlab-language versions was performed in comparison with both analytical and theoretical models taken from existing literature.[7,9] Validation was performed using experimental data taken from the PA Hilton laboratory model[10,11] described in Section II.A.5.

II.A.5. *Laboratory Model*

Schematics for the laboratory demonstration cooling tower are shown in Figure 3. Students use a heater with known output as the basis for their First Law (energy conservation) equations, and enforce mass conservation of water by analyzing the performance of the cooling tower system using a psychrometric chart[12] to look up the expected properties of moist air at a pressure corresponding to an elevation of 1500 m (Salt Lake City, UT has an elevation of about 4200 ft or 1300 m). Further details of the assumptions, procedures, and equations used are provided in the student lab manual. The most current version can be obtained from the first author or downloaded online.[11]

II.A.6. *Implementation in GFSSP*

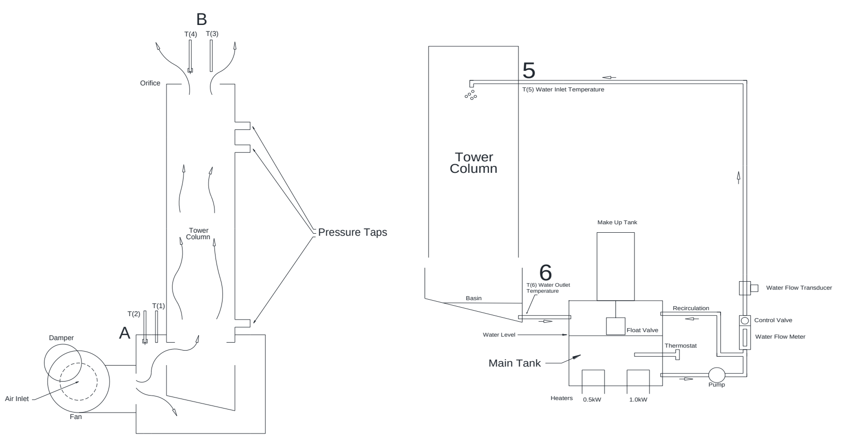

Figure 3. Schematics for Cooling Tower Laboratory Demonstration, University of Utah Department of Mechanical Engineering, courtesy of J. DeSutter. LEFT: Air flow through the cooling tower (bottom to top); RIGHT: Water loop through the cooling tower (top to bottom).

A cooling tower model with 7 nodes and 6 branches has been created as a GFSSP input file. The user provides a guess value for water outlet temperature (which may not be cooler than the entering wet bulb temperature of the air), and providing assumed conditions for the air outlet so that air inlet conditions can be provided to each node through a simple linear interpolation. The tower's characteristic $K_m A$ must be known in advance, or calculated through the procedure shown in Figure 1, available as a Matlab/Octave program.[13] Because the heat losses through the walls of the tower are neglected, $T_{wb,out} = T_{wb,in}$. The numerical solver determines water outlet conditions to a desired level of convergence using the process shown in Figure 2, beginning with the top node (water inlet and air exit), and marching in the direction of the water loop.

GFSSP is already equipped with the capability to enforce conservation laws by fluid species and to calculate and provide species concentrations at the nodes,[2] which for this application corresponds directly to ω. Mass conservation is enforced for air, i.e. O_2 and N_2 molecules (dry air), and for water both in the 'water' loop and in the air loop in the form of water vapor, so that for the entire system $m_{w,in} = m_{w,out}$. At steady state:

$$\dot{m}_{w,evaporated} = \dot{m}_a(\omega_{out} - \omega_{in}) = \dot{m}_{loss}$$

so that water loss is equal to the amount of water that leaves with the air (i.e. the water evaporation rate). This is also the quantity of makeup water that must provided to a real cooling tower in operation.

III. Vapor Cycles

III.A. Application: Vapor Compression Refrigeration Cycle

The development of the vapor compression refrigeration cycle drove the expansion of mechanically driven cooling in the 20th century. It is a classic problem used in teaching thermodynamics and other heating, ventilation, air-conditioning, & refrigeration-related sciences. In its ideal form, it consists of:

- A compressor which takes a refrigerant from its saturated vapor state to a much higher temperature and pressure
- A condenser where the refrigerant rejects heat to its surroundings (the 'warm' medium, which must be below the temperature of the refrigerant entering the condenser for heat transfer to occur)
- An isenthalpic expansion valve which relieves the high pressure of the refrigerant
- An evaporator where the refrigerant absorbs heat from its surroundings (the 'cold' medium, which must be above the local temperature of the refrigerant, although it is colder than the 'warm' medium).

III.A.1. Laboratory Model

A real vapor compression system in operation is more likely to have refrigerant entering the compressor as a slightly superheated fluid already, will have pressure drops in all branches, will likely allow the fluid to cool into a slightly compressed liquid before entering the expansion valve, and the throttling process may not be perfectly isenthalpic.[9] Nevertheless, the simplified mathematical model described in undergraduate thermodynamics texts[9] is an excellent predictor of the performance of a vapor compression refrigeration system. The components of a vapor compression refrigeration demonstration setup at the University of Utah are shown in Figure 4. For the purposes of illustration, the 'warm' medium and 'cold' medium are the same in this case, that is, the atmospheric air in the room.

III.A.2. Mathematical Model

Figure 4. Vapor Compression Laboratory Demonstration, University of Utah Department of Mechanical Engineering

The components above, when modeled as ideal devices (i.e. reversible compressor, condenser, and evaporator; constant enthalpy expansion valve), have the following first law forms after simplifications:

Compressor, isentropic compression:
$w = h_{in} - h_{out} \approx v_{in}(\Delta P)$
Condenser, constant pressure heat rejection:
$q = h_{in-h_{out}}$
Expansion valve, isenthalpic:
$h_{in} \approx h_{out}$
Evaporator, constant pressure heat addition:
$q = h_{in} - h_{out}$
Same simplification as for the condenser above, opposite sign (heat is *added* to the working fluid rather than rejected from it).

Students analyzing the performance of the vapor-compression refrigeration system use property tables[9] to look up the expected properties of the refrigerant, hydrofluorocarbon 134-a (R-134a). Details of the assumptions, procedures, and equations used are provided in the student lab manual which can be obtained from the first author or downloaded online.[11]

III.A.3. Implementation in VTASC

The model for the vapor compression system was built using existing components within the current GFFSP version through the VTASC interface, as shown in Figure 5. The case study illustrated here is based on an experimental data obtained by students using the equipment shown in Figure 4. The compressor is represented as a mass source in the branch labeled with $\dot{m}$. The condenser (labeled) is represented as a heat exchanger where heat is rejected by the working fluid. The isenthalpic expansion is represented by a Joule Thomson valve (branch 34) which was adjusted to match the characteristics of the needle valve in the experimental setup. The evaporator (labeled) is represented similarly to the condenser where heat is now entering the system as the working fluid changes phase. The cyclic boundary node option[2] is activated at node 12, a node capturing the state of the fluid at the exit of the compressor. Additional branches represent the piping in the bench scale system. Validation was performed using experimental data taken from the laboratory model described in Section III.A.1.

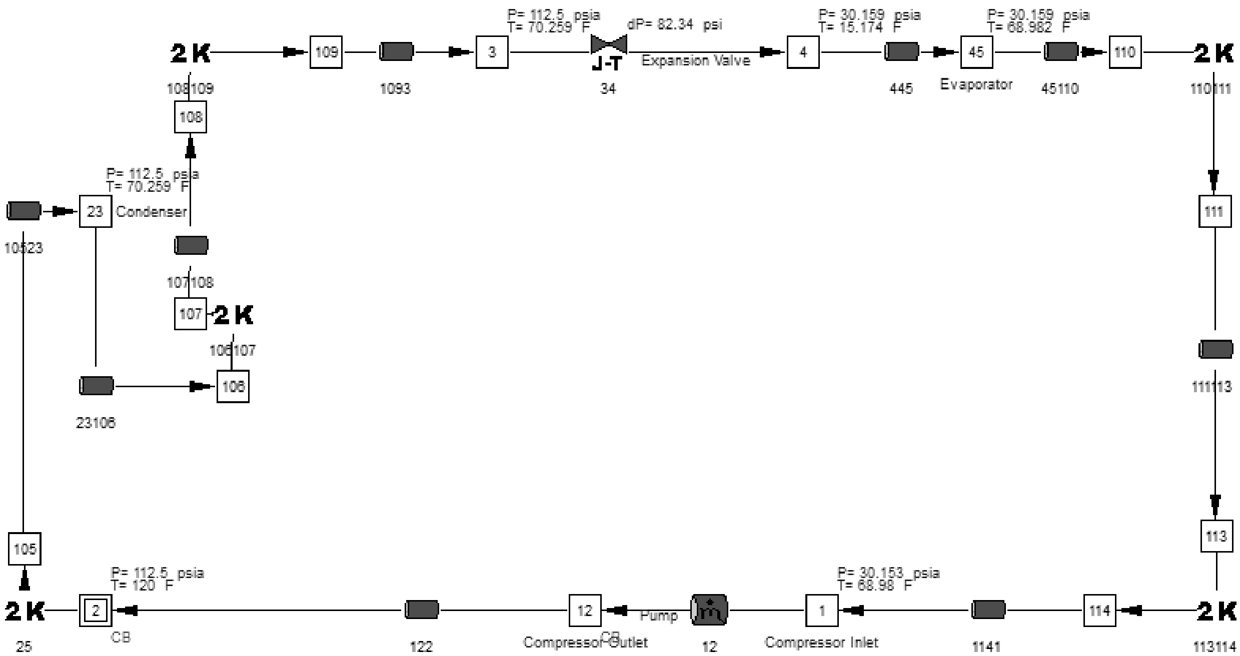

Figure 5. VTASC GFSSP model of a vapor compression refrigeration system, courtesy of C. Ursachi

III.B. Application: Rankine Power Cycle

The Rankine steam cycle is the technical basis for almost all thermoelectric power generation systems, the most common type of electricity generation in land-based power stations. It is a classic problem used in teaching power and energy sciences. In its simplest ideal form, it consists of:

- A pump which takes a working fluid from its saturated liquid state to a much higher pressure compressed liquid state
- A heat exchanger called a boiler with a high-temperature heat source, or 'hot' medium, which takes the working fluid to a superheated vapor state at the same pressure
- A turbine which allows the fluid to expand, releasing pressure and creating shaft work by driving the rotors as it flows through, and
- A heat exchanger called a condenser where the working fluid rejects heat to a 'cold' medium (for a power generation station, river water or chilled water produced by a cooling tower or cooling pond).

A number of modifications are commonly used to increase the work output of the cycle and its overall efficiency, including reheating and regeneration, supercritical steam generation, or low condenser pressures. A real steam cycle in operation is more likely to have water entering the pump as a compressed liquid, will have pressure drops in all branches, and will have additional losses due to heat transfer and fluid friction such as those in a non-isentropic turbine.[9]

This paper describes only an ideal cycle with a single-stage turbine, but a regenerative cycle model (one open feedwater heater) has also been developed in VTASC and more detailed models may be developed in GFSSP using existing components in VTASC and/or customized user subroutines, or obtained by contacting the authors.

III.B.1. Mathematical Model

The components above, when modeled as ideal devices, have the following simplified first law forms:

Pump, isentropic compression: $w = h_{in} - h_{out} \approx v_{in}(\Delta P)$
Boiler, constant pressure heat addition: $q = h_{out} - h_{in}$
Turbine, isentropic expansion: $w = h_{in} - h_{out}$
Same simplification as for the pump above, opposite sign (work is done *by* working fluid rather than on it).
Condenser, constant pressure heat rejection: $q = h_{out} - h_{in}$
Same simplification as for the boiler above, opposite sign (heat is *rejected* from the working fluid rather than added to it).

III.B.2. Implementation in VTASC

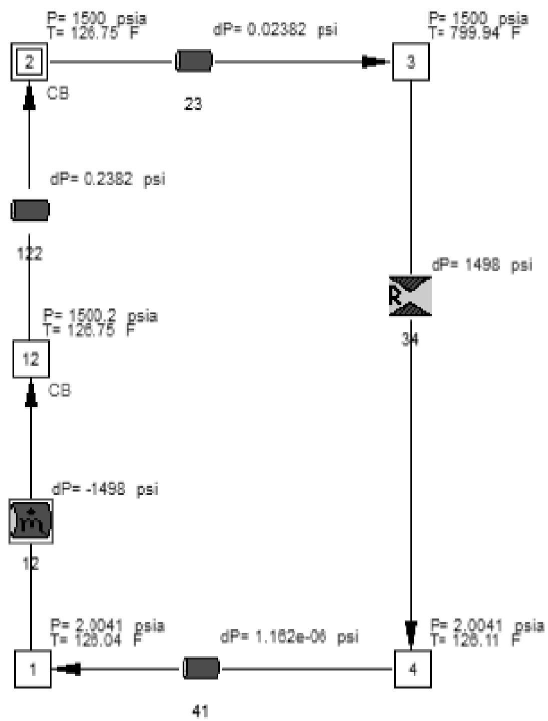

Figure 6. VTASC GFSSP model of a simple Rankine steam cycle, courtesy of C. Ursachi

The model for the Rankine steam cycle power system was built using existing components within the current GFSSP version through the VTASC interface, as shown in Figure 6. The case study illustrated here is based on a theoretical problem presented by Çengel and Boles[9] and was verified with the numbers provided in the associated instructor's manual. The pump is represented as a mass source in the branch labeled with $\dot{m}$. The boiler is represented as a heat exchanger (branch 23) where heat is added to the working fluid. The turbine is represented as a flow restriction 34 such that the enthalpy change of the fluid represents the energy leaving the system in the form of work (or power, at a given instant). The condenser is represented similarly to the boiler (branch 41) where heat is rejected by the working fluid. The cyclic boundary node option[2] is activated at node 12, a node capturing the state of the fluid at the exit of the pump supplying feedwater to the boiler.

IV. Conclusions

This paper described three new applications for the general purpose fluid network software tool, GFSSP: a cooling tower, a vapor-compression refrigeration system, and a Rankine cycle power generation system. These systems demonstrate the flexibility of the GFSSP modeling system and its capabilities in representing some important physical processes, both in NASA applications and in energy systems at the Earth's surface: two-phase flow and phase transformations. These example problems will add to the examples provided with the GFSSP instructional literature and provides pressure,temperature, and species concentrations at designated locations, or nodes, within a fluid network based on a finite volume formulation of thermodynamics and conservation laws. The theoretical basis for the construction of the models, i.e. energy and mass conservation, was described, and the results of the specific models created have demonstrated that it is possible to represent a bench-scale cooling tower and vapor-compression refrigeration system using GFSSP. A number of teaching and research applications are now possible based on these results, and those planned by the authors are described in Section V below.

V. Future Work

The cooling tower model will be used by students in the Fall 2017 Thermodynamics II course at the University of Utah in completing their laboratory assignment corresponding to Section II.A.5, as an aid for predicting the expected performance of the laboratory cooling tower and for analyzing their experimental results. Students will also be able to simulate the performance of the same cooling tower in a sea-level atmosphere (higher ambient pressure) to investigate the effect of altitude on its performance, or in a different climate (higher humidity) to investigate the effect of ambient wet bulb temperature on its effectiveness.

The vapor-compression refrigeration system model will be used by thermodynamics students in completing their laboratory assignment corresponding to Section III.A.1, as an aid for predicting the expected performance of the refrigeration system and for analyzing their experimental results. The compressor is non-isentropic and in fact rejects heat to the atmosphere, so that the working fluid's specific entropy will decrease as it passes through. Students typically have difficulty relating the ideal cycle model to the operation of a real system, and we hypothesize that the use of GFSSP will allow them to think more deeply about the performance of each individual device in the system, thereby improving their understanding of its operation as a whole.

The Rankine power cycle model will be used by thermodynamics students to check their own homework problems. As additional modifications are added, such as multiple feedwater heaters and a reheat stage, GFSSP may be used more extensively in analyzing these complex systems in both undergraduate and graduate thermodynamics courses.

The cooling tower model will be used next as a dynamic (transient) simulation so that its performance in cooling can be studied over time in a variety of realistic conditions, in which the ambient dry bulb and wet bulb are changing. This has implications for: optimal control of cooling systems, changes in cooling tower performance with a changing climate, and water consumption for power generation. Previous work by the author[14] has assumed a rough correlation between water withdrawals and consumption for power generation based on basic knowledge of the cooling system type,[15] but adding a physical representation of the link between power output, ambient conditions, and water losses could greatly reduce the amount of uncertainty inherent in this type of analysis. The dynamic GFSSP model will also be compared against a neural network model that has been developed in Matlab and trained on manufacturer-provided data, to investigate the relative benefits or drawbacks in terms of complexity, computational time, and accuracy between a physics-based model and a machine learning-based model.

The Rankine power cycle model and the cooling tower model, if simulated simultaneously, would provide a valuable model for this large, complex system. The Rankine cycle model may also be adapted to simulate an Organic Rankine Cycle, useful for low-grade waste heat recovery, provided that the working fluid's properties are accessible from, or provided to, GFSSP. Planned developments for the GFSSP modeling system as a whole include a newly designed visual interface and an interface for user subroutines written in languages other than Fortran, which will reduce the learning curve and make it even more friendly toward integration into undergraduate teaching programs and research use in other fields.

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