Vapor-Compression Refrigeration Simulation and Tutorial

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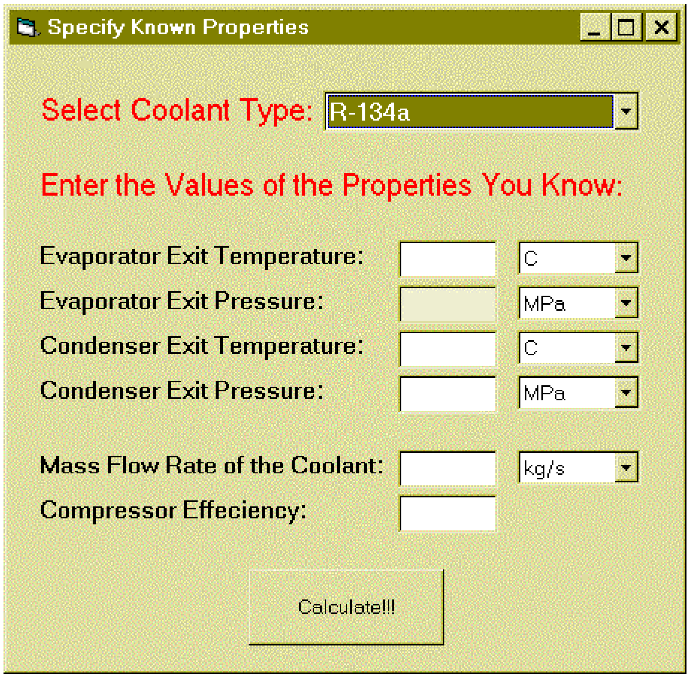
Abstract

Calculation intensive courses lead to the need to integrate computer technology into the classroom, especially in courses such as Applied Thermodynamics at the University of Portland (ME 332). ME 332 is the second in the series of thermodynamics courses offered at the University of Portland; therefore the opportunity arises for the implementation of interactive tools for ease of calculations. Once the students have mastered the concepts and ability to perform the necessary manual calculations, computer programs can be used to allow the students to study more advanced topics in the material without being bogged down in the calculations. To ease the considerable calculations involved in solving vapor-compression refrigeration (VCR) cycle problems in the course, a text-based computer program was written, complete with property evaluation for 3 three substances, by L.J. Genik and C.W. Somerton at Michigan State University. This program has recently been revised to be compatible with the Microsoft Windows operating environment prevalent today in engineering software. In addition, a fourth refrigerant, R-134a, was added to account for the addition of new refrigerants in use today. Another modification made to the program was the addition of a tutorial for the thermal system analysis of a VCR cycle. This tutorial emulates the general solution methodology used in the course and reinforces the concepts with the students. The program is available via current web pages for the described course.

Introduction

The evaluation of thermodynamic systems can become a long and tedious process, though an important one for students to learn and master. Several cycles are continually taught in applied thermodynamics courses such as the Rankine cycle for steam power systems, the Brayton cycle for gas turbine systems, vapor-compression for refrigeration systems. Within the applied thermodynamics course at the University of Portland, these cycles are taught along with deviations from these cycles. A thorough investigation into the operation of these cycles can be facilitated with the use of the computer to ease the property evaluation process. There are several good, commercially available programs and solvers for implementing such solutions; however, for economic reasons we have chosen to developed an in-house program. Beyond the economics of the situation, it is also the belief of the authors that value exists in writing and understanding thoroughly the 'black box' being used by students for solving problems.

The computer program utilizes equations of state and fundamental thermodynamic relations to perform a systems analysis. The first law of thermodynamics is used to evaluate the energy transfers for the ideal vapor compression refrigeration (VCR) cycle with either the operating temperatures or pressures known, the mass flow rate and the isentropic efficiency of the compressor, Figure 1. The program was originally written in FORTRAN and has been recently converted to Microsoft Visual Basic to allow for a graphical user interface (GUI). Along with this conversion, a tutorial was added which defines the working components of the system and steps through the methodology for solving cycles using VCR as an example. The program allows for the user to do repeated calculations of the VCR cycle which would allow the student to begin to gain insight into how various changes effect the heat transfer, coefficient of performance (COP), and required work.



Select Coolant Type: R-134a

Enter the Values of the Properties You Know:

Evaporator Exit Temperature: C
Evaporator Exit Pressure: MPa
Condenser Exit Temperature: C
Condenser Exit Pressure: MPa

Mass Flow Rate of the Coolant: kg/s
Compressor Effeciency:

Figure 1
Input Dialogue Box

Property Evaluation

The program gives the user the option to work with one of four refrigerants: steam, R-22, R-12, and R-134a. Both R-22 and R-12 are no longer endorsed as common refrigerants, but are still in use in older systems. For this reason and the ability to compare, both were left as options in the revision of the program. The properties are evaluated from accepted and well-published equations of state and Maxwell's fundamental relations. See references Cengal[1], Reynolds[3], Thelen[4], Downing[2], and Tillner-Roth[5].

The Basic Cycle

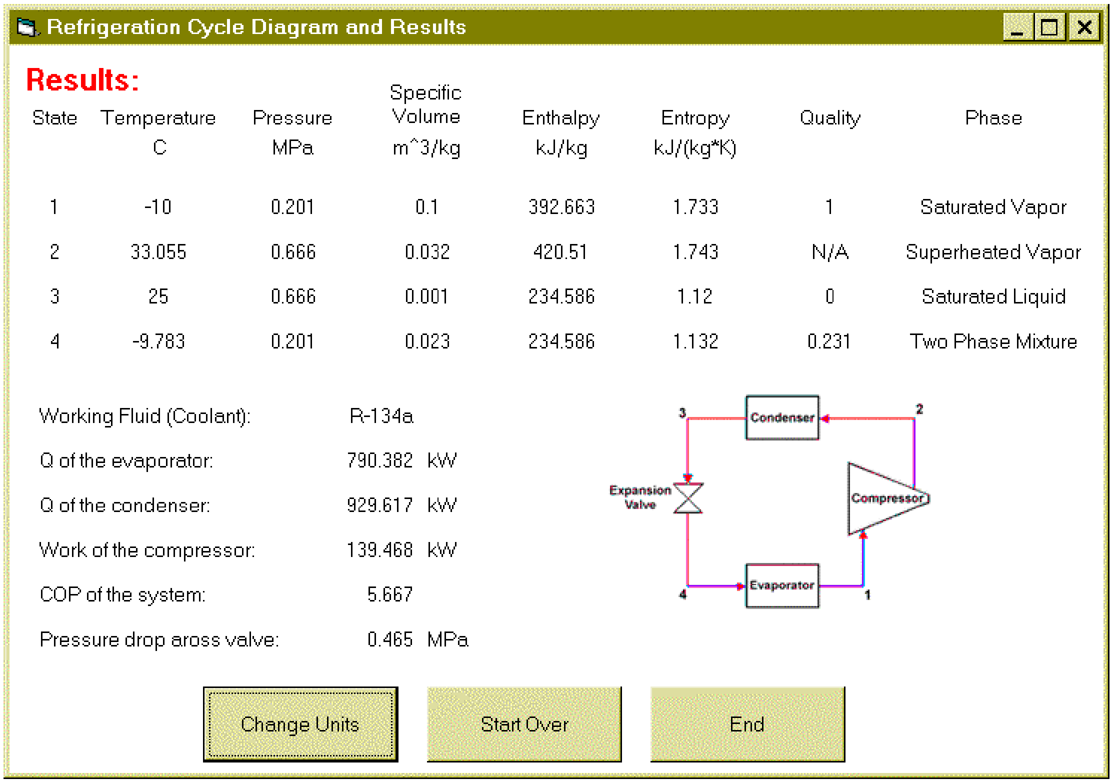
The ideal vapor compression refrigeration cycle that is utilized is outlined in Cengal[1] and is summarized here.

1-2 Isentropic compression in a compressor
2-3 Constant pressure, heat rejection in a condenser
3-4 Throttling in an expansion device
4-1 Constant pressure, heat adsorption in an evaporator

The solution method assumes saturated vapor at state 1 and saturated liquid at state 3. Hence, with this outline of the cycle a problem is completely specified if the operating temperatures or pressures are known. The compression process may also be modeled with an isentropic efficiency and a mass flow rate must be specified for the calculation of power and rate of heat rejection or adsorption.

Final Output and Unit Conversion

The calculations internal to the program are done in SI units except where the equations of state are only specified in English units (see Downing[2]) and then appropriate unit conversions are made to maintain dimensional homogeneity. The input and output of the program may be in any mix of units (SI or English) selected from a pull down menu. The output is presented in a tabulated form that is emphasized in lecture as a general format for cycle analysis. After the program has been executed, the user may convert the output to any units desired by making an appropriate selection from a pull down menu, Figure 2.



Results:

State	Temperature C	Pressure MPa	Specific Volume m^3/kg	Enthalpy kJ/kg	Entropy kJ/(kg*K)	Quality	Phase
1	-10	0.201	0.1	392.663	1.733	1	Saturated Vapor
2	33.055	0.666	0.032	420.51	1.743	N/A	Superheated Vapor
3	25	0.666	0.001	234.586	1.12	0	Saturated Liquid
4	-9.783	0.201	0.023	234.586	1.132	0.231	Two Phase Mixture

Working Fluid (Coolant):	R-134a	
Q of the evaporator:	790.382	kW
Q of the condenser:	929.617	kW
Work of the compressor:	139.468	kW
COP of the system:	5.667	
Pressure drop aross valve:	0.465	MPa

Figure 2
Final Calculation Screen

Overview of Tutorial

The tutorial gives the user the option to step through several screens that explain the refrigeration system and then to solve a problem. Each screen gives a brief explanation of either the system or a component, then each step of the problem solving methodology is explained while a problem is being solved. The tone of the tutorial is taken to be conversational and the screens, which explain various operations of the VCR system, should be read with this in mind. The directed audience of the tutorial is the learning, undergraduate thermodynamics student, to whom certain fundamental concepts and laws may not be second nature yet. The following gives some excerpts from the tutorial, (italicized titles are taken directly from the program).

Purpose of a Refrigeration System

There are many applications for refrigeration systems and the use of these systems is widely used in personal, commercial, and industrial applications. In industry, maintaining the required temperature for the transport and storage of food uses varied forms of refrigeration. The cooling load on a system for a refrigerated train car will be different than for a refrigerated truck or for refrigerated storage. Furthermore, the climate will affect the selection as well~~:~~; will the train be moving through the Rocky Mountains or will it be traveling through an arid desert climate? In this type of application, refrigeration is required all the time. In an air conditioning application, refrigeration is only required part of any given year depending on climate.

Rating Refrigeration Systems

To accomplish the cooling desired in refrigeration systems, several different combinations of equipment and refrigerants (the fluid used by the system, whose thermodynamic properties make the system work) are used. In general, these systems may be compared to each other by looking at the ratio of the desired output to required input. Refrigeration systems require a work input to have a desired cooling load, which leads to a coefficient of performance (COP), defined as the cooling load divided by the work input. The COP is a non-dimensional measure of the performance of the cycle. The higher the COP, the better the system is. The maximum cannot exceed the maximum set forth by a Carnot cycle operating in reverse.

The Vapor Compression Cycle

The vapor compression cycle is based on using the thermodynamic properties of the refrigerant to transfer heat from a colder source (inside your house, for the example of a home air conditioner) to a warmer source (outside your house, for example). In order to simplify the explanation and calculations, we will study the ideal cycle. Each of the assumptions made will be outlined during the calculations. This refrigeration system is physically comprised of the following hardware: a compressor, condenser, expansion valve and evaporator.

The Compressor

The compressor raises the pressure of the refrigerant from a saturated vapor state to a superheated vapor state. During this process, ideally modeled as isentropic, the temperature of the refrigerant is raised to well above that of the warm source.

The Condenser

Entering the condenser, a heat exchanger, at a higher temperature than the warm source surrounding the condenser, the refrigerant is cooled to a saturated liquid. This process releases the heat removed from the cold source to the warm source. It is assumed that there is no pressure loss across the condenser.

The Expansion Valve

This device throttles the pressure of the incoming saturated liquid to the evaporator pressure, resulting in a low-quality saturated mixture. This process lowers the temperature of the refrigerant to a level below that of the cold source.

The Evaporator

The actual cooling takes place here, where the low quality saturated mixture refrigerant is heated by the cold source to the state of saturated vapor. By entering the evaporator at a lower temperature than the cold source, the refrigerant removes heat from the cold source. This heat is carried by the refrigerant and expelled to the warm source. It is assumed that there is no pressure loss across the evaporator.

An Example Solution

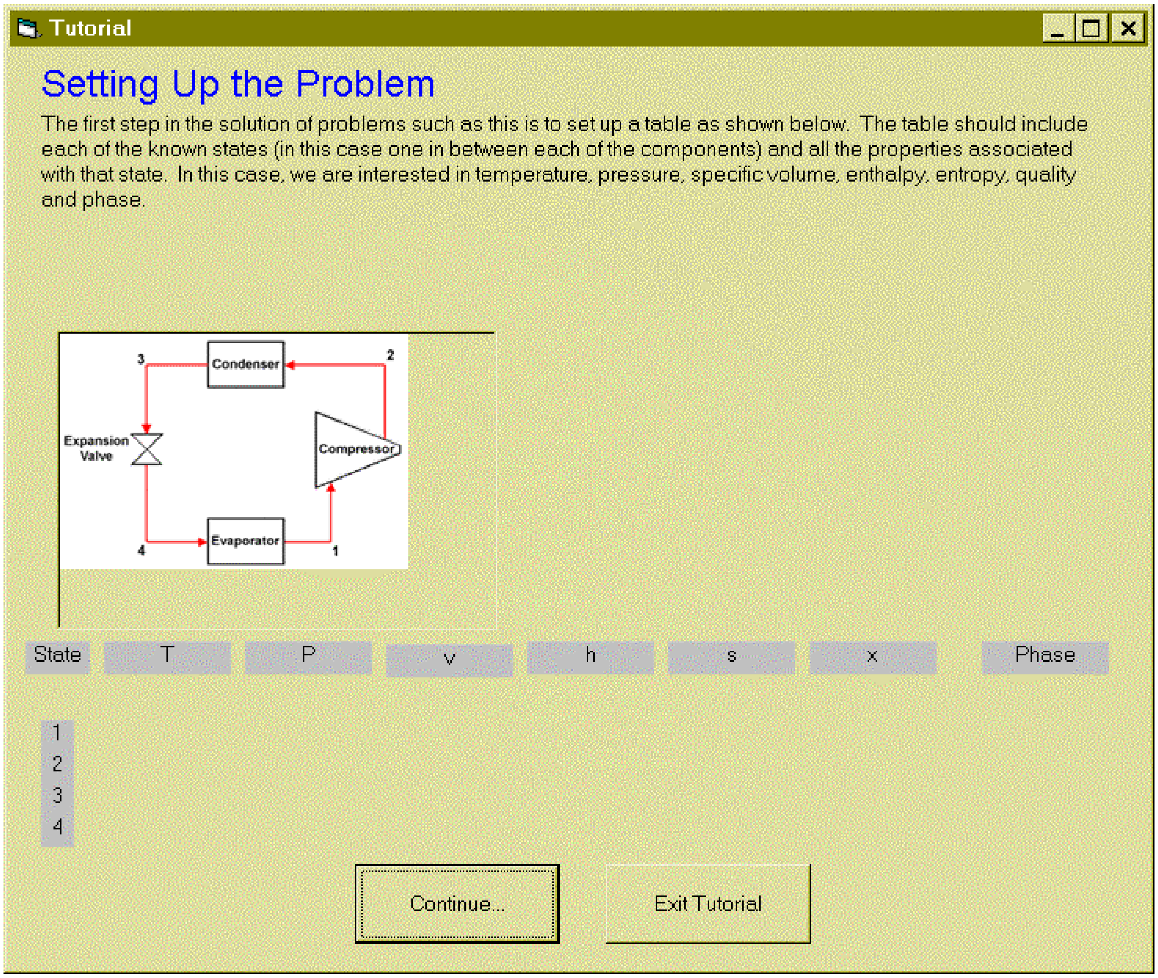
To demonstrate how to solve problems that involve the vapor compression refrigeration cycle, an example problem will be solved. Each step will be described, any assumptions will be explained, and hints will be given to help make these types of problems easier to solve.

The Example Problem from Cengal and Boles[1]

A refrigerator uses refrigerant-12 as the working fluid and operates on an ideal vapor compression refrigeration cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine the rate of heat removal from the refrigerated space and the power input to the compressor, the heat rejection rate to the environment, and the COP of the refrigerator.

Setting Up the Problem

The first step in the solution of problems such as this is to set up a table as shown below. The table should include each of the known states (in this case one in between each of the components) and all the properties associated with that state. In this case, we are interested in temperature, pressure, specific volume, enthalpy, entropy, quality and phase, Figure 3.



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State	T	P	v	h	s	x	Phase
1							
2							
3							
4							

Figure 3
Suggested Tabulated Format

Input the Known Values

Next, input the known values into the table. In this case, we only know the two operating pressures of the system, 0.14 and 0.8 MPa. Since we assume no pressure loss over the evaporator or condenser, the pressures of states 1 and 4 are the same, as are 2 and 3. In this case, states 1 and 4 are on the low-pressure side (0.14 MPa) and states 2 and 3 are on the high pressure side (0.8 MPa).

Solve for Known Saturation Values

In the ideal vapor compression refrigeration cycle, it is assumed that the refrigerant is a saturated fluid at the condenser outlet and a saturated gas at the evaporator outlet. Assuming this and knowing the pressures at this point, we can use property tables for the refrigerant to find the temperature, specific volume, enthalpy and entropy. We can also fill in the values for quality and the phase information in our table. In our situation, the values for the saturated states of our refrigerant at our given pressures are filled into our table below.

Process Assumptions

There are two more assumptions that are necessary in order to solve our ideal case. The first is that isentropic compression is performed between states 1 and 2. The second assumption is that the throttling process between states 3 and 4 is isenthalpic. Using these two assumptions, we can determine the entropy for state 2 and the enthalpy for state 4. These values are then used as input in our table.

Solving for the Remaining States

Now that we have two properties for each of our remaining unknown states (pressure and entropy for state 2 and pressure and enthalpy for state 4), we can solve for the remaining unknown properties for those states. Again, refrigerant tables are used to find unknown properties and then they are put into our table. The properties of states 2 and 4 for our situation are in the table below.

Solution of the Problem

Now that we have all the known properties for our system, solving the problem is just a matter of solving the appropriate relationships. We need to solve for the rate of heat removal from the refrigerated space and the power input to the compressor, the heat rejection rate to the environment, and the COP of the refrigerator.

Rate of Heat Removal and Power Input to the Compressor

We will be using the first law of thermodynamics for each control volume that is analyzed. The heat exchangers are assumed to have no work associated with the process and the compressor is assumed to be adiabatic. The work or heat transfer will be specified as into or out of the system. To solve for rate of heat removal from the refrigerant and the power input to the compressor, we will use the known mass flow rate of the refrigerant (0.05 kg/s) and the known enthalpy values at each state. Below are the reduced forms of the first law that we will use to solve these problems. The value of the rate of heat removal from the refrigerated space turns out to be 5.53 kW and the power input to the compressor is 1.54 kW.

$$\dot{Q}_L = \dot{m}(h_1 - h_4)$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1)$$

Rate of Heat Rejection into the Environment

The next value we need to solve for is the rate of heat rejection into the environment. Again, we will use the known mass flow rate of the refrigerant and the known enthalpy values at each state to solve for this value. The reduced form of the first law used for this solution is shown below. The rate of heat rejection into the environment for our situation is solved to be 7.07 kW. This value could also be determined by applying the first law to the cycle as a whole, as shown below.

$$\dot{Q}_H = \dot{m}(h_2 - h_3)$$

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in}$$

COP of the Refrigeration System

Finally, we need to solve for the COP of the refrigerator. As defined previously, the COP of the system is defined as the cooling load divided by the work input. This is shown in the relationship below and turns out to be 3.59 for this particular system. This is equivalent to saying that the refrigerant removes 3.59 units of energy from the refrigerated space for each unit of electric energy it consumes.

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}}$$

Summary

So, after finding the properties at each state, we used the first law of thermodynamics for each device to find that the rate of heat removal from the refrigerated space is 5.53 kW, the power input to the compressor is 1.54 kW, the rate of heat rejection into the environment is 7.07 kW, and the COP for the system is 3.59. All of this was determined from only knowing the two operating pressures, the mass flow rate of the refrigerant, and by making a few assumptions. This same problem could have been solved if the operating temperatures would have been known rather than the pressures. The procedure outlined here is applicable to any thermodynamic cycle and is generally accepted as a solution methodology. The use of the computer program eases the burden of property evaluation and allows for expanded analysis of the cycles.

Example Assignment

Several variations to the VCR cycle may be investigated with this program: different refrigerants or changes in operating pressures and temperatures, and the analysis of the effects on net power and heat transfer rates by each of these variations. An example of one such assignment is included here along with the required graphical results from the students. The students are also required to do one hand calculation of one cycle to verify the outcome of the program.

Determine the effect of the condenser pressure on the COP of an ideal vapor-compression refrigeration cycle. Assume the evaporator pressure is maintained constant at 120 kPa and the mass flow rate of refrigerant is 1 kg/s. Calculate the COP of the refrigeration cycle for the following condenser pressures: 400, 500, 600, 700, 800, 900, 1000, 1400 kPa. Plot the COPs against the condenser pressure.

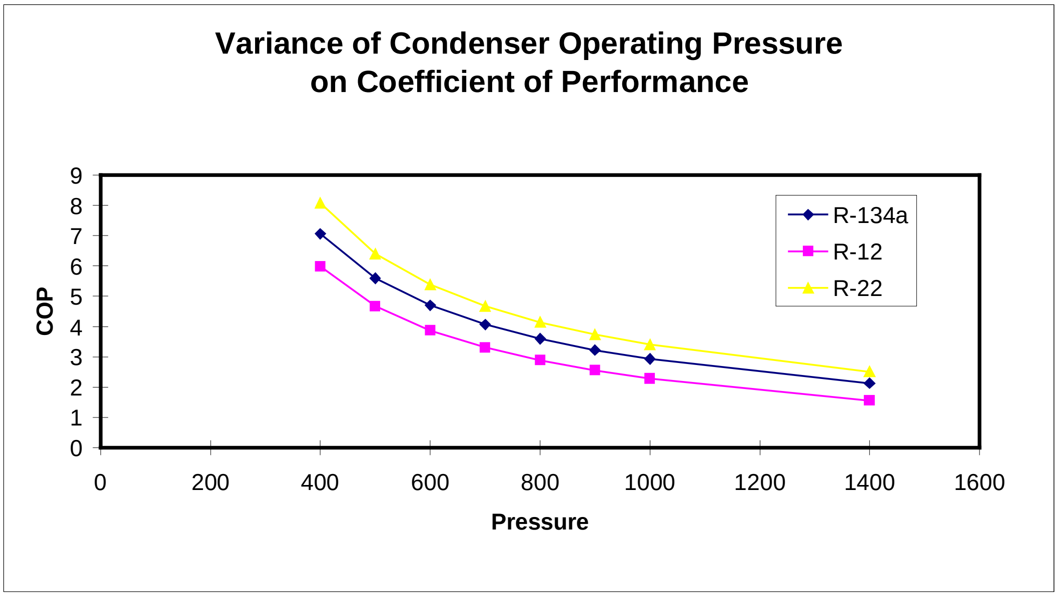

Figure 4
Sample Assignment Solution

Student Feedback

In general, the students found the program to easy to use and understand. Several students commented on the simplicity of the program operation and ease of calculations, allowing further understanding of the system as a whole. Suggestions for improvement ranged from the addition of more refrigerants to including more cycles. Both are issues to be given all due consideration. Students, who explored the tutorial, found it to be very helpful and easy to understand. The program it is available to students via the instructors web site (www.egr.up.edu/contrib/genik/me332.html).

Conclusions and Recommendations

Students must be adept at calculations by hand to fully appreciate the capabilities of this program. The computer program allows for students to begin to gain understanding of a cycle analysis beyond the burden of property evaluation which students have a tendency to become mired down in. This type of program, for instance, allows the students to gain an appreciation for how a change in refrigerant can affect the overall operation of a cycle.

Future considerations to this program would be to add more refrigerants such as Genetron-404a, a drop-in replacement for R-22. Also, the addition of cascading systems and the versatility to build a system that deviates from the standard VCR system are slated for future versions.

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