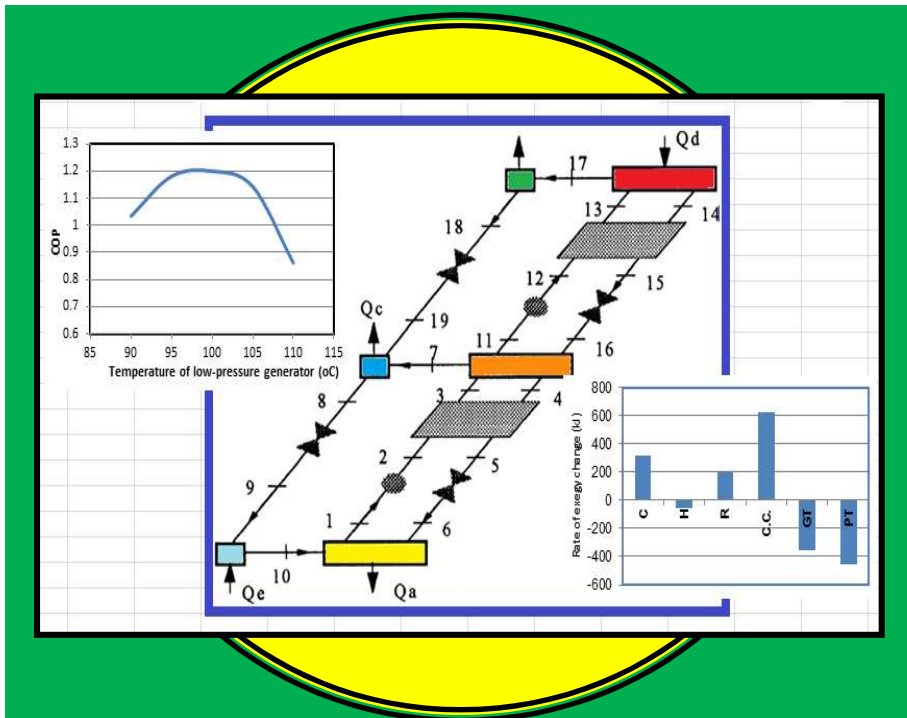


Thermodynamic Analyses and Optimisation of Energy-Conversion Systems Using Excel



Mohamed M. El-Awad

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Preface

The devastating effects of large-scale energy utilisation make proper design and operation of energy-conversion and utilisation systems more critical than ever before. Since the design methodologies of these systems are mainly based on applying the principles of engineering thermodynamics, these principles must be properly understood by engineering students. However, thermodynamics is usually seen as a difficult subject because it involves numerous concepts and laws some of which are rather abstract. Thermodynamic analyses also require the physical properties of the fluids involved to be determined at different phases, temperatures, and pressures. Although the traditional method of using property tables and charts is important for introducing the basic concepts of the subject, it is not suitable for conducting parametric sensitivity analyses that help the students to understand these concepts better. The use of tables and charts is also not suitable for design optimisation analyses of energy-conversion systems that aim to maximise their economic feasibility and minimise their environmental impact. In this respect, computer-aided methods can improve the learning process by helping the students to easily apply the basic principles of the subject in relevant design analyses of complex energy-conversion systems. Moreover, these methods can make the thermodynamic models developed for these systems more realistic compared to the traditional models that usually adopt many idealisations and simplifying assumptions.

Although the commercial computer applications that are used for industrial and research analyses can also be used for educational purposes, they are not the ideal method either because of their cost and complexity or because they don't allow white-box modelling of the systems to be analysed. On the other hand, developing the required thermodynamic models using standard computer programming requires good programming skills and takes a long time. A perfect solution to this dilemma is offered by the general-purpose spreadsheet applications such as Microsoft Excel. Compared to the dedicated commercial software, the main advantage of Excel is its wide availability on personal computers and simplicity of use. As a modelling platform for engineering analyses, Excel provides a rich library of mathematical functions and powerful graphic tools for data visualisation. From an educational point of view, the Excel-based modelling platform allows the students to build white-box models from the basic principles. Although Excel itself does not provide functions for determining fluid properties which are necessary for thermodynamic analyse, such functions can be developed as custom functions with the Visual Basic for Applications (VBA) programming language that comes with Microsoft Applications. The automation of property calculations enables the students to deal with iterative solutions and time-consuming parametric studies and the Solver add-in that comes with Excel enables the students to perform constrained and multi-variable optimisation analyses of energy-conversion systems.

This book presents an Excel add-in called Thermax that provides property functions for twenty-nine ideal gases, water and superheated steam, twenty-eight synthetic and natural refrigerants, two aqua solutions for vapour-absorption refrigeration, humid air for

psychrometric analyses, and atmospheric air at various temperatures. By using Thermax functions, the book shows how Excel can be used to deal with the analyses of different types of thermodynamic cycles that include the basic gas and vapour power cycles, the simple, multi-stage compression and cascade vapour-compression refrigeration cycles, and the single-effect and two-effect vapour-absorption refrigeration cycles. Two chapters of book show how the add-in functions can be used for psychrometric analyses of air-conditioning systems and processes and for the development of a general sheet for combustion analyses. The last two chapters of the book deal with thermoeconomic optimisation analyses of energy-conversion systems by considering two examples which are the air-bottoming cycle and the gas-turbine cycle with inlet-air cooling.

Most of the cases considered in the book have been adopted from popular textbooks and published work so that the results obtained by Thermax functions can be verified. While relevant exercises are provided at the end of Chapters 2 to 5, more challenging exercises and mini projects are given in the last appendix of the book. The book has been written for educational purposes, but it is hoped that it can also be useful to the researchers and practicing engineers in this area.

Acknowledgements

The development of Thermax would not have been possible without benefitting from the efforts of many other people who have made the fruits of their efforts available in the open literature or the internet. In this respect, my special gratitude goes to the Mechanical Engineering Department at the University of Alabama (USA) whose initiatives both inspired and helped me throughout the many years I took to write of this book. My gratitude and appreciation also go to the College of Applied Sciences in Sohar (Oman) who provided the financial support that helped me to prepare most of the material covered in the book. I am also indebted the unfailing support received from my colleagues and students in Malaysia, Sudan, and Oman, and hope that they find this book a fair repay. Last, but not least, my thanks and gratitude go to my beloved family for their tolerance and unfailing support desperately needed to complete the work.

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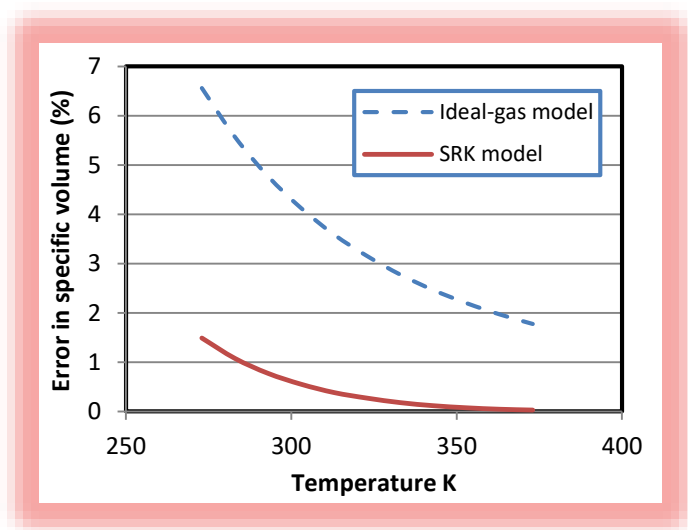
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Nomenclature

Property	Units
Air-fuel ratio	-
Concentration (of an absorption solution)	%
Density	Kg/m ³
Dry-bulb temperature	°C
Diffusivity	m ² /s
Dew-point temperature	°C
Dynamic viscosity	μPa.s
Enthalpy (specific)	kJ/kg
Enthalpy of formation (molar)	kJ/kmol
Entropy (absolute molar)	kJ/kmol.K
Enthalpy (molar)	kJ/kmol
Entropy (specific)	kJ/kg.K
Entropy of saturated liquid solution	kJ/kg.K
Entropy of saturated vapour solution	kJ/kg.K
Entropy change with temperature (ideal gas)	kJ/kg.K
Entropy change with temperature (molar)	kJ/kmol.K
Gibbs function of formation (molar)	kJ/kmol
Heat of vaporization of fuel	kJ/kg
Humidity (specific or absolute)	-
Heating value of fuel (higher and lower)	kJ/kg.K
Humidity (relative)	%
Internal energy (specific)	kJ/kg
Internal energy (molar)	kJ/kmol
Kinematic viscosity	m ² /s
Prandtl number	-
Pressure	kPa
Quality (dryness fraction)	-
Relative pressure	-
Refrigerant pressure	kPa
Relative specific volume	-
Refrigerant temperature	°C
Saturation pressure	kPa
Saturation temperature	°C
Specific volume	m ³ /kg
Specific heat at constant pressure	kJ/kg.K
Specific heat at constant pressure (molar)	kJ/kmol.K
Surface tension	mN/m
Temperature	°C
Temperature (wet-bulb)	°C
Temperature (absolute)	K
Thermal conductivity	mW/(m.°C)
Volumetric expansion coefficient	°C ⁻¹
Velocity of sound	m/s

Chapter 1

Introduction



Thermodynamic analyses of the energy-conversion cycles that involve phase changes of the working fluid, like the Rankine cycle, require the determination of fluid properties at different phases of the fluid. For these analyses computer-aided methods are more convenient than traditional methods that use property tables and charts. For the cycles that involve gases and do not involve phase changes computer-aided methods are also advantageous because they allow the application of the variable specific-heat method of analysis instead of the approximate constant specific-heat method which is less accurate. This chapter reviews the principles of thermodynamic analyses of energy-conversion systems and discusses the advantages of computer-aided methods for such analyses. The chapter also highlights the capabilities of Microsoft Excel as a modelling platform for thermodynamic analyses and thermoeconomic optimisation of energy-conversion systems and introduces Thermax, the Excel add-in that is used to conduct the various analyses presented in this book.

1.1. A brief review of thermodynamics

The principles of engineering thermodynamics help us to evaluate and optimise the performance of the various energy-conversion systems. To evaluate the energy transfer between an energy-conversion system and its surroundings and account for the various losses that usually occur in any energy-conversion or energy-transfer process, the three basic thermodynamic principles are the conservation of mass, the conservation of energy (the first-law of thermodynamics), and the second-law of thermodynamics. For illustration, consider the air-compression system shown on Figure 1.1 that has two stages of compression separated by an intercooler.

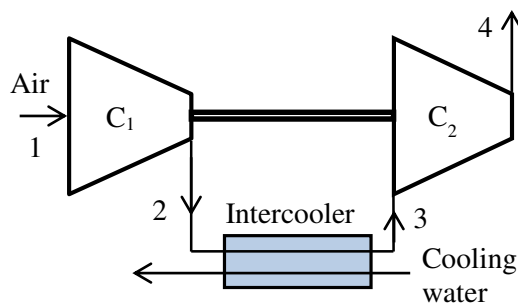


Figure 1.1. Schematic diagram of a two-stage air compressor with inter-stage intercooling

Air enters the system at a temperature T_1 and pressure P_1 . The first-stage compressor, C_1 , compresses the air adiabatically to state 2, after which it enters the intercooler where its temperature is reduced to T_3 . The second-stage compressor, C_2 , then increases the air pressure to P_4 and temperature to T_4 . Figure 1.2 shows the compression process on a temperature-entropy diagram. The required compression work is divided between the two compressor stages depending on their compression ratios and there is a certain value of the intermediate pressure (P_i) that minimises the total work. The principles of thermodynamics help us to determine this optimum intermediate pressure.

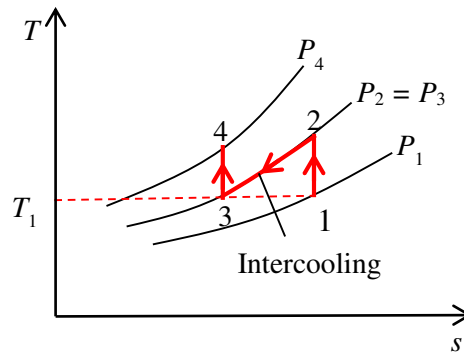


Figure 1.2. T - s diagram of a two-stage air compressor with inter-stage intercooling

Treating the two compression stages as steady-flow processes, and neglecting changes in kinetic and potential energy, the first-law of thermodynamics leads to [1]:

$$q - w = (h_{out} - h_{in}) \quad (1.1)$$

Where q and w are the amounts of heat transfer and work transfer per unit mass flow rate of air, respectively, and $(h_{out} - h_{in})$ is the resulting enthalpy change in the stage. Equation (1.1) adopts the usual sign convention that heat into the system is positive, while work into the system is negative. Assuming the compression processes in both stages to be adiabatic ($q=0$) and reversible means that the processes are isentropic as shown on Figure 1.2. Using an average value of the specific heat for air at constant pressure (c_p), the compression work per unit mass flow rate of air in stage 1 (w_1) and in stage 2 (w_2) can be determined from Equation (1.1) as follows:

$$w_1 = -(h_2 - h_1) = -c_p(T_2 - T_1) \quad (1.2)$$

$$w_2 = -(h_4 - h_3) = -c_p(T_4 - T_3) \quad (1.3)$$

Therefore, the total compression work in both stages (w_{total}) is given by:

$$w_{total} = w_1 + w_2 = -c_p \left[(T_2 - T_1) + (T_4 - T_3) \right] \quad (1.4)$$

Assuming perfect intercooling, i.e., $T_3 = T_1$, and rearranging Equation (1.4):

$$w_{total} = c_p T_1 \left[\left(1 - \frac{T_2}{T_1} \right) + \left(1 - \frac{T_4}{T_3} \right) \right] = c_p T_1 \left[2 - \left(\frac{T_2}{T_1} \right) - \left(\frac{T_4}{T_3} \right) \right] \quad (1.5)$$

Since the two compression processes are assumed to be isentropic and the specific heat c_p for air to be constant, for an ideal gas the temperature ratios in Equation (1.5) can be converted into pressure ratios by using the second law of thermodynamics as follows:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \quad (1.6)$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3} \right)^{\frac{k-1}{k}} \quad (1.7)$$

Where k is the ratio of specific heats ($k=c_p/c_v$); c_v is the specific heat for air at constant volume. Assuming that there is no pressure loss in the intercooler, i.e., $P_3 = P_2 = P_i$, substitution from Equations (1.6) and (1.7) into Equation (1.5) gives:

$$w_{total} = c_p T_1 \left[2 - \left(\frac{P_i}{P_1} \right)^{\frac{k-1}{k}} - \left(\frac{P_4}{P_i} \right)^{\frac{k-1}{k}} \right] \quad (1.8)$$

To see how the total compression work varies with the intermediate pressure P_i , let us consider the specific case in which $T_1 = 300\text{K}$, $P_1 = 100\text{ kPa}$, and $P_4 = 900\text{ kPa}$. Using Equation (1.8), the total compression work in the system was calculated for different values of P_i and the result is shown on Figure 1.3. The figure shows that the value of P_i at which the total compression work is minimal is around 300 kPa. Increasing or decreasing P_i from this value will increase the compression work.

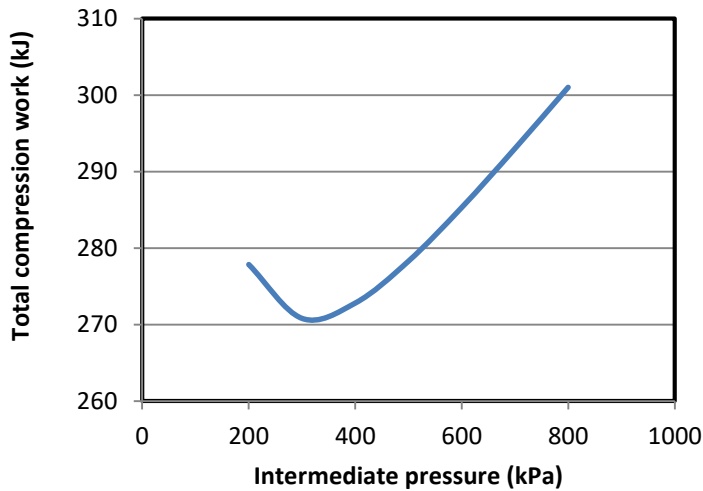


Figure 1.3. Variation of the total compression work with the intermediate pressure

The principles of thermodynamics are also useful for performance evaluation and optimisation of the more complicated power and refrigeration systems. For example, consider the regenerative steam-turbine power plant shown on Figure 1.4.

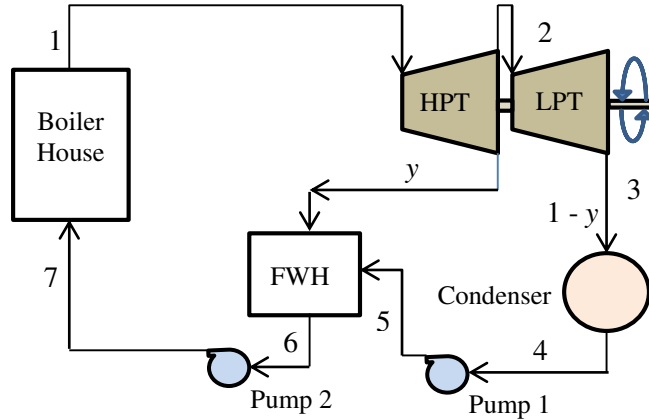


Figure 1.4. Schematic diagram of a regenerative steam-turbine power plant

This plant consists of a boiler house for producing superheated steam, a high-pressure steam turbine (HPT), a low-pressure steam turbine (LPT), a condenser, an open feed-water heater (FWH) and two feed-water pumps. A fraction of the steam (y) is extracted after the HPT for preheating the feed-water before going back to the boiler house. The extracted steam reduces the work output from plant, but it also reduces the amount of heat added in the boiler and its net effect is to increase the thermal efficiency of the plant. There is also a certain extraction pressure for the steam at which the plant's thermal efficiency attains a maximum value. As shown below, the principles of thermodynamics can be used to determine this optimum steam-extraction pressure.

The net specific work output from the plant (w_{net}) is given by:

$$w_{net} = w_{out} - w_{in} \quad (1.9)$$

Where w_{out} is the total specific work output from the two turbines and w_{in} is the total work input to the two pumps which are given by:

$$w_{out} = w_{HPT} + w_{LPT} \quad (1.10)$$

$$w_{in} = w_{P1} + w_{P2} \quad (1.11)$$

Where w_{HPT} and w_{LPT} are the specific work output from the high-pressure turbine and the low-pressure turbine, respectively, and w_{P1} and w_{P2} are the specific work input in pump

1 and pump 2, respectively. Assuming the two turbines and the two pumps to be adiabatic and neglecting the changes in kinetic and potential energies, the work output or input for each device can be determined from the enthalpy difference across the device. Per each kg of steam generated in the boiler, these are given by:

$$w_{HPT} = (h_1 - h_2) \quad (1.12)$$

$$w_{LPT} = (1 - y)(h_2 - h_3) \quad (1.13)$$

$$w_{P1} = (1 - y)(h_5 - h_4) \quad (1.14)$$

$$w_{P2} = (h_7 - h_6) \quad (1.15)$$

Mass and energy balance over the open feed-water heater gives:

$$yh_2 + (1 - y)h_5 = 1 \times h_6 \quad (1.16)$$

The specific heat input to the boiler (q_{in}) is determined by the relevant enthalpy change as follows:

$$q_{in} = (h_1 - h_7) \quad (1.17)$$

Therefore, the thermal efficiency of the plant (η) can be calculated from:

$$\eta = w_{net} / q_{in} \quad (1.18)$$

Both w_{net} and η depend on the fraction of steam extracted for regeneration (y); which in turn depends on the extraction pressure (P_2). Figure 1.5 shows the variation of y and η with P_2 for an ideal cycle in which $P_1 = 15$ MPa, $T_1 = 600^\circ\text{C}$, and $P_4 = 10$ kPa. The figure shows that the cycle's efficiency attains a maximum value of 45.55% when P_2 is about 1000 kPa.

It should be mentioned that the working fluid in the above power plant changes its phase from subcooled liquid water to superheated steam in the boiler, becomes a saturated mixture of water and steam in the low-pressure turbine, and returns to subcooled water in the condenser. Therefore, appropriate property relationships, tables, or charts are needed in order to determine the working fluid enthalpy at different states.

The principles of thermodynamics are also needed for the analyses of air-conditioning systems and processes and the analyses of the processes that involve combustion and other chemical reactions. For such analyses, thermodynamics provides the basic relationships needed to quantify the effects of fluid mixing and chemical reactions on the

properties of the working fluids and on the transfer of energy and effluents to or from the energy-conversion system.

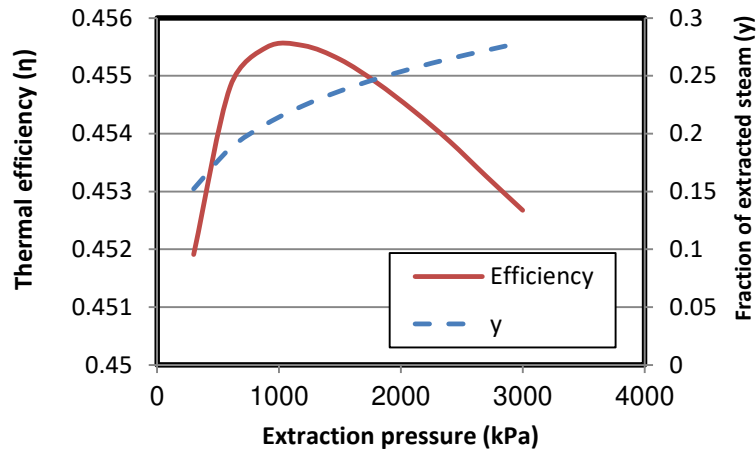


Figure 1.5. The effect of intermediate pressure (P_2) on the fraction of extracted steam (γ) and thermal efficiency (η) of a regenerative steam-turbine power plant

1.2. Advantages of computer-aided thermodynamic analyses

Apart from saving time and effort and eliminating possible human errors, computer-aided analyses of energy-conversion systems offer a number of advantages over the traditional methods of analyses that use property tables and charts. An important advantage of computer-aided methods with respect to thermodynamic analyses is their ability to give more realistic results by avoiding unnecessary simplification of the models and by using more accurate estimations of fluid properties. Moreover, they offer reliable techniques for iterative solutions and optimisation analyses. In what follows, these advantages are illustrated by means of relevant examples.

A. Avoiding excessive simplification of the model

In many situations, traditional analytical methods excessively simplify the analytical models; which makes their results grossly deviate from the behaviour of real systems. A good example of this situation is given by the models of internal-combustion (IC) engines. Traditional air-standard models of IC engines, such as the Otto cycle and the Diesel cycle, neglect heat-transfer and friction losses, treat the combustion process as heat-addition from an external source, and use constant specific heats. These assumptions enable the engine processes to be represented by simple closed-form relations for calculating the amount of heat added to the engine and net work from the engine. However, air-standard models usually overestimate the engine's output and thermal efficiency. By comparison, computer-aided models of IC engines, such as those described by Ferguson [2] that take into consideration the geometrical as well as the thermodynamic characteristics of the engines, closely mimic the behaviour of actual IC engines. Therefore, these models can be used to investigate the effect of important design and

operation factors such the ignition or injection timing on the engine performance or the effect of engine speed on the specific fuel consumption. However, the formulation of these models leads to a set of ordinary differential equations that need to be solved simultaneously by using a numerical solver such as the Newton-Raphson method.

B. Accurate representation of fluid properties and processes

The behaviour of real gasses and vapours is frequently modelled by using the following ideal-gas law:

$$P\tilde{v} = R_u T \quad (1.19)$$

Where P is the absolute pressure of the gas, \tilde{v} is the molar specific volume, R_u is the universal gas constant, and T is the absolute temperature of the gas. The ideal gas law can be used with reasonable accuracy for determining the specific volume of a superheated vapour, but when the temperature approaches the saturation line, the value of the specific volume determined by the ideal-gas law departs significantly from the actual volume. Figure 1.6 shows the deviations from the tabulated values by those obtained from the ideal-gas law for refrigerant R134a at 0.2 MPa. The figure shows that the error of the ideal-gas law is more than 2% even at high temperatures and increases as the temperature approaches the saturation value.

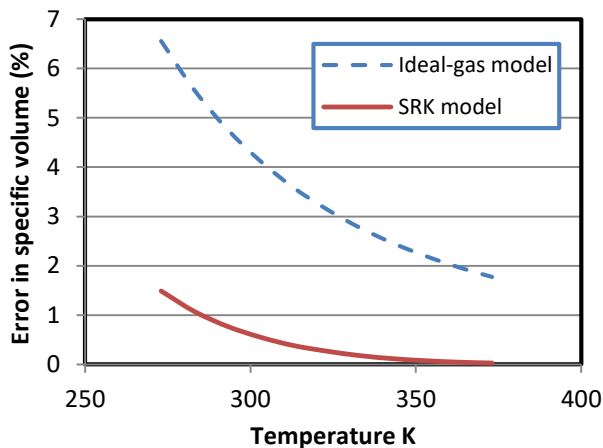


Figure 1.6. Errors in the specific volume of R134a by the ideal-gas law and the SRK equation of state

More accurate estimates can be obtained by using the Soave-Redlich-Kwong (SRK) equation of state [1]:

$$P = \frac{R_u T}{\tilde{v} - b} - \frac{a\alpha}{\tilde{v}(\tilde{v} + b)} \quad (1.20)$$

Where the constants a , b and α are fluid-dependent. For the same case described above, Figure 1.6 shows that the accuracy of the SRK equation remained higher than 99% even close to the saturation line. However, since the SRK equation is implicit in \tilde{v} , it cannot be used directly to determine the specific volume, but has to be solved iteratively. A number of standard iterative procedures (e.g. Newton-Raphson method) can be used to solve the equation, but they are not convenient for hand calculations.

C. Dealing with iterative solutions and optimisation analyses

Thermodynamic analyses involving iterative solutions and optimisation analyses suit computer-aided methods more than manual methods even for simple systems. A good example of thermodynamic analyses that require iterative solutions is the determination of the adiabatic flame temperature by a first-law analysis of the combustion process. Optimisation analyses are needed for determining the best design for a certain energy-utilisation systems such as the optimum intermediate pressure for an air-compression system, the optimum steam-extraction pressure for a regenerative Rankine cycle, and the optimum intermediate pressures for multi-stage and cascade refrigeration systems. While simple optimisation analyses that involve a single design parameter can be performed by means of calculus techniques and graphic tools, optimisation analyses of more complex systems that involve multiple variables require the use of computer-aided techniques.

1.3. Excel as a modelling platform for thermodynamic analyses

Microsoft Excel provides a rich library of built-in functions and powerful graphical tools. Considering its wide availability, the simplicity of its user-interface, and the flexibility of its graphical tools, it is being increasingly used as a teaching aid in various engineering subjects [3-8]. Although Excel is mostly used for dealing with simple computer-aided operations like matrix inversion and multiplication, it is equipped with other tools that make it a capable modelling platform for more challenging types of “What-if” and optimisation analyses. Two of these tools are the Goal Seek command and the Solver add-in. The Visual Basic for Applications (VBA) programming language that comes with Microsoft Office can be used for developing customised user-defined functions (UDFs) and add-ins for thermodynamic analyses. The Developer ribbon of Excel also allows the use of macros that remove the tedium of parametric studies and repetitive calculations.

The main limitation of Excel as modelling platform for thermodynamic analyses is the lack of built-in functions for fluid properties, but this problem could be solved by developing suitable add-ins. The *Thermotable* add-in developed by the Mechanical Engineering Department at the University of Alabama determines the thermodynamic properties of ideal gases, water and superheated steam, and four refrigerants R134a, R22, R410A, and R407C [9-12]. Goodwin [13] also developed an educational Excel add-in, called *TPX* (Thermodynamic Properties for Excel), that determines the properties of five gases (H_2O , H_2 , O_2 , N_2 , CH_4) and refrigerant R-134a. A number of property add-ins have also been developed for research and industrial applications [14, 15]. The American National Institute of Standards and Technology (NIST) developed *REFPROP* that

provides thermophysical properties of various refrigerants and their mixtures [16]. An open-source alternative to *REFPROP*, called *CoolProp*, was developed by Bell [17] at the University of Liege. Optimized Thermal Systems also developed a commercial alternative add-in to *REFPROP* called *XProps* [18].

This book presents an educational add-in, called *Thermax*, that enables Excel to be used for thermodynamic analyses of various types of energy-conversion systems. *Thermax* provides property functions for seven groups of working fluids that are used in energy-conversion systems that include:

- Twenty-nine ideal gases,
- Water and superheated steam,
- Twenty-eight refrigerants for vapour-compression refrigeration (VCR) systems,
- Lithium-bromide and ammonia aqua solutions for vapour-absorption refrigeration (VAR) systems,
- Humid air for psychrometric analyses,
- Various types of fuels and chemically-reacting substances,
- Air at standard atmospheric pressure but various temperatures.

In addition to its seven groups of fluid-property functions, *Thermax* provides a small group of user-defined functions that are useful for general thermofluid analyses. These include two data interpolation functions and a Newton-Raphson solver for non-linear equations such as the SRK equation of state.

1.3. Closure

Chapter 2 describes the fluid property functions provided by *Thermax* in more details and shows how these functions can be used in Excel's formulae for thermodynamic analyses. Appendix A and Appendix B supplement Chapter 2 by listing the ideal-gases, refrigerants and chemical reactants supported by *Thermax* and providing the equations used to determine the thermodynamic properties of ideal gases, superheated refrigerants, and humid air. The three chapters that follow Chapter 2 illustrate the use of *Thermax* functions for the analyses of basic power and refrigeration systems. Chapters 3 and 4 that deal with the analyses of power cycles give examples of analysing the Brayton cycle, the Otto cycle, the Rankine cycles with and without regeneration, the combined Brayton-Rankine cycle, and the organic Rankine cycle. Chapter 5 deals with the analyses and optimisation of single-stage, multi-stage compression, and cascade VCR cycles using refrigerant R134a. Appendix C extends the treatment of Chapter 5 by verifying *Thermax* functions for refrigerants properties and by presenting an analysis of a cascade VCR system with the two ozone-friendly refrigerants, R507A and R23.

Chapter 6, 7, and 8 show how *Thermax* can be used to deal with thermodynamic analyses in which the working fluids are mixtures of gaseous or liquid substances. Chapter 6 deals with the analyses of psychrometric processes and illustrates the use of *Thermax* property functions for design analyses of air-conditioning systems. Chapter 7 focuses on

combustion analyses and describes the development of a general Excel sheet for steady-flow combustion analyses. Appendices D and E extend the general Excel sheet to deal with combustion in closed systems and second-law analyses of combustion processes. Chapter 8 illustrates the use of Thermo functions for the analyses of single-effect and double-effect VAR cycles using ammonia-water and lithium-bromide-water solutions.

The last two chapters of the book show how Thermo property functions and the two solution methods offered by Solver enable the Excel-based modelling platform to deal with optimisation analyses of fluid-thermal systems in general and energy-conversion systems in particular. Chapter 9 compares the thermodynamic and thermo-economic optimisation analyses of the air-bottoming cycle and illustrates the advantage of the Evolutionary method of Solver when dealing with optimisation analyses with multiple design parameters. Chapter 10 that deals with thermo-economic optimisation analyses of the gas-turbine cycle with inlet-air cooling highlights the influence of the thermodynamic model of the system to be optimised and shows that the two solution methods offered by Solver can give the designer more than one optimum solution to consider. The chapter also demonstrates the advantage of the Excel-based model that can take into consideration the deficiencies of the various system components.

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Thermax provides Excel with custom functions that determine the key thermo-physical properties for 29 ideal gases, water and superheated steam, 28 vapour-compression (VC) refrigerants, two binary solutions used in vapour-absorption (VA) refrigeration, humid air for air-conditioning applications, various fuels and chemically reacting substances, and atmospheric air at various temperatures. To help the user select the suitable property function, Thermax functions are divided into seven groups such that each group deals with one substance or similar substances and each group of functions are given a common indicative prefix; e.g. “Gas” for ideal gases, “Wat” for water/steam, and “Ref” for VC refrigerants. The name of each function also indicates its output and input properties. This chapter explains the name style adopted for Thermax functions in more details and shows how it can be utilised by Excel’s function wizard to help the user find the required function without having to memorise the names of all the add-in functions. The chapter also describes the procedure for installing the add-in and using its functions in Excel’s formulae for thermodynamic analyses.

2.1. The name style for Thermax property functions

Consider the two Thermax functions shown on Figure 2.1. The first function shown on Figure 2.1.a determines the enthalpy of saturated water at a pressure of 500 kPa and quality of 0.8, while that shown on Figure 2.1.b determines the entropy of a superheated refrigerant R134a at a pressure of 200 kPa and temperature of 50°C.

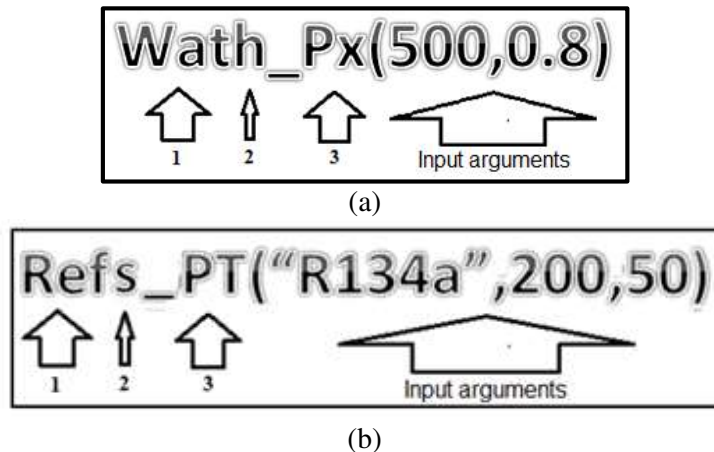


Figure 2.1. Examples of Thermax functions

Figure 2.1 shows that the name of a function consists of the following three parts:

1. The first three letters (1) refer to the function’s group, i.e., “**Wat**” for water/steam and “**Ref**” for vapour-compression refrigerants.
2. The fourth letter (2), which is followed by an underscore, refers to the function’s output property, i.e., “**h_**” for enthalpy and “**s_**” for entropy.
3. The letters after the underscore (3) refer to the function’s input parameter(s), i.e., “**Px**” for pressure and quality and “**PT**” for pressure and temperature (in °C).

Figure 2.1 also shows the required input parameters for the two functions. While first function (**Wath_Px**) requires two input properties, which are the pressure (500 kPa) and quality (0.8), the second function (**Refs_PT**) requires three input parameters which are the refrigerant name (“R134a”), the pressure (200 kPa), and the temperature (50°C).

For the other groups “**Gas**” stands for ideal gases, “**Psy**” for psychrometric analyses, “**LiB**” and “**Nh3**” for the two binary solutions used in VA refrigeration, “**Chm**” for fuels and chemically reacting substances, and “**Air**” for air at atmospheric pressure. Table 2.1 gives more examples for the add-in functions with their intended usage.

Table 2.1. Examples of Thermax property functions from different groups

#	Thermax function	Output
1	Gash_TK(“Air”,350)	Determines the enthalpy (h) for air at 350K
2	GasTK_h(“Air”,500)	Determines the absolute temperature for air given its enthalpy ($h=500$ kJ/kg)
3	Wats_Tx(150,0.5)	Determines the entropy (s) of saturated water at a temperature of 150°C and quality of 0.5
4	Wath_PT(90,150)	Determines the enthalpy of superheated steam at 90 kPa and 150°C
5	RefPsat_T(“R134a”,-5)	Determines the saturation pressure (P_{sat}) for refrigerant R134a at -5°C.
6	PsyRh_PTSh(101,30,0.001)	Determines relative humidity (ϕ) of air at 101 kPa, 30°C, and specific humidity (ω) of 0.001 kg/kg
7	Airdv_T(25)	Determines the dynamic viscosity of air at standard atmospheric pressure and 25°C.
8	Chm_f1(“C6H6”,“M”)	Returns the molar mass for benzene (C_6H_6)
9	Chm_f3(“N2”,“M”)	Returns the molar mass for nitrogen (N_2)
10	LiBh_TX(20,80)	Determines the enthalpy of water-lithium bromide solution at 20°C and 80% concentration.

The following points should also be noted regarding Thermax and its name style:

1. The add-in adopts only the SI system of units, e.g., pressure unit is kPa.
2. In the Gas-group, the absolute temperature is represented by “TK” while in the other groups the temperature in °C is represented by “T”.
3. Three groups involve more than one substance and, therefore, the functions of these groups require the name of the substance as the first input parameter. These groups are the Gas-group, the Ref-group, and the Chm-group.
4. The input and output properties in most of the functions are represented by one or two letters, e.g. **Gash_TK** and **GasTK_h**, but some properties are represented by three letters like the saturation pressure and saturation temperature, which are

represented by P_{sat} and T_{sat} in the **Wat** and **Ref** groups. Another example is the density of atmospheric air in the **Air**-group which is represented by **Airrho**.

2.2. Property functions provided by Thermax

The functions provided by each group are described below.

2.2.1. Functions for ideal gases (Gas)

This group of Thermax functions determine the ideal-gas properties for the 29 gasses listed in Appendix A based on the established ideal-gas relationships [1]. The group provides the 12 functions listed in Table 2.2.

Table 2.2. Functions for thermodynamic properties of ideal gases

#	Function	Input [Unit]	Output [Unit]
1	GasM	Gas name	Molar mass, M [kg/kmol]
2	Gascp_TK	Gas name, T [K]	Specific heat, c_p [kJ/kg.K]
3	Gash_TK	Gas name, T [K]	Specific enthalpy, h [kJ/kg]
4	Gasu_TK	Gas name, T [K]	Specific internal energy, u [kJ/kg]
5	Gass0_TK	Gas name, T [K]	Entropy component, s^0 [kJ/kg.K]
6	GasPr_TK	Gas name, T [K]	Relative pressure, P_r [-]
7	Gasvr_TK	Gas name, T [K]	Relative volume, v_r [K]
8	GasTK_h	Gas name, h [kJ/kg]	Absolute temperature, T [K]
9	GasTK_u	Gas name, u [kJ/kg]	Absolute temperature, T [K]
10	GasTK_s0	Gas name, s^0 [kJ/kg.K]	Absolute temperature, T [K]
11	GasTK_Pr	Gas name, P_r [-]	Absolute temperature, T [K]
12	GasTK_vr	Gas name, v_r [-]	Absolute temperature, T [K]

The first five functions in Table 2.2 determine the molar mass (M), specific heat (c_p), enthalpy (h), internal energy (u), and the part of entropy change due to temperature change (s^0), respectively. The two functions that follow, **GasPr_TK** and **Gasvr_TK**, determine the relative pressure (P_r) and relative specific volume (v_r) of the ideal gases, respectively. The last five functions in the table are inversion functions that determine the temperature of the ideal gas from its enthalpy (h), internal energy (u), temperature-dependent entropy change (s^0), relative pressure (P_r) or relative specific volume (v_r).

With the exception of the first function, **GasM**, all the functions in this group involve the gas absolute temperature as an input or output parameter. Note that the temperature in the names of all the functions in this group is represented by “TK”. An auxiliary function named “**Gas_data**”, not shown in the table, stores the values of the four coefficients a_0 , a_1 , a_2 , and a_3 in Equation (A.1) for the 29 gases [1]. The same function is needed by the third function in the combustion and chemical reactions group (**Chm_f3**) to determine the properties of the gases involved in a combustion or chemical reaction process.

2.2.2. Functions for water and superheated steam (Wat)

This group of functions that determine the thermo-physical properties of water and superheated steam can be divided into two subgroups: (a) functions for the properties of saturated water/steam mixture and (b) functions for the properties of superheated steam. Properties of subcooled liquid water can be taken as the corresponding values of saturated liquid water at the given temperature [1].

a) Properties of saturated water/steam mixture

The 20 functions in this subgroup do not use mathematical formulae, but store and interpolate the tabulated data for saturated water provided by ASHRAE [2]. Table 2.3 shows the input and output parameters of the 10 property functions that determine the properties of saturated water/steam mixtures at a given temperature with their relevant units. The corresponding 10 custom functions that provide properties of saturated water-steam mixture at a given pressure are listed in Table 2.4. Properties of water as saturated liquid or saturated vapour can be obtained from the functions number 2 to 9 by assigning the value of the quality x as 0 or 1, respectively.

Table 2.3. Property functions for saturated water/steam at a given temperature

#	Function	Input [Unit]	Output [Unit]
1	WatPsat_T	T [°C]	Saturation pressure, p_s [kPa]
2	Watv_Tx	T [°C], x [-]	Specific volume, v [m ³ /kg]
3	Watu_Tx	T [°C], x [-]	Specific internal energy u [kJ/kg]
4	Wath_Tx	T [°C], x [-]	Specific enthalpy, h [kJ/kg]
5	Wats_Tx	T [°C], x [-]	Specific entropy, s [kJ/kg.K]
6	Watcp_Tx	T [°C], x [-]	Specific heat c_p , [kJ/(kg·K)]
7	Watk_Tx	T [°C], x [-]	Thermal cond., k [mW/(m·K)]
8	Watdv_Tx	T [°C], x [-]	Viscosity, μ [Pa·s]
9	Watvs_Tx	T [°C], x [-]	Velocity of sound, [m/s]
10	Watst_T	T [°C]	Surface tension, [mN/m]

Table 2.4. Property functions for saturated water/steam at a given pressure

#	Function	Input [Unit]	Output [Unit]
1	WatTsat_P	P [kPa]	Saturation temperature, T_s [°C]
2	Watv_Px	P [kPa], x [-]	Specific volume, v [m ³ /kg]
3	Watu_Px	P [kPa], x [-]	Specific internal energy u [kJ/kg]
4	Wath_Px	P [kPa], x [-]	Specific enthalpy, h [kJ/kg]
5	Wats_Px	P [kPa], x [-]	Specific entropy, s [kJ/kg.K]
6	Watcp_Px	P [kPa], x [-]	Specific heat c_p , [kJ/(kg·K)]
7	Watk_Px	P [kPa], x [-]	Thermal cond., k [mW/(m·K)]
8	Watdv_Px	P [kPa], x [-]	Viscosity, μ [Pa·s]
9	Watvs_Px	P [kPa], x [-]	Velocity of sound, [m/s]
10	Watst_P	P [kPa]	Surface tension, [mN/m]

b) Properties of superheated steam

There are 8 functions in this subgroup that determine the thermodynamic properties of superheated steam as shown in Table 2.5. The first four functions determine the specific volume (v), internal energy (u), enthalpy (h), and entropy (s) of superheated steam given the pressure and temperature according to the formulae provided by Irvine and Liley [3]. The remaining four functions are inverse functions that use iteration to determine the temperature, enthalpy, or entropy from the pressure and another property.

Table 2.5. Properties of superheated steam given the pressure and another property

#	Function	Input [Unit]	Output [Unit]
1	Watv_PT	$P, T [^{\circ}\text{C}]$	Specific volume, v [m^3/kg]
2	Watu_PT	$P, T [^{\circ}\text{C}]$	Specific internal energy u [kJ/kg]
3	Wath_PT	$P, T [^{\circ}\text{C}]$	Specific enthalpy, h [kJ/kg]
4	Wats_PT	$P, T [^{\circ}\text{C}]$	Specific entropy, s [$\text{kJ}/\text{kg}\cdot\text{K}$]
5	WatT_Ph	$P, h[\text{kJ}/\text{kg}]$	Temperature, T [$^{\circ}\text{C}$]
6	WatT_Ps	$P, s[\text{kJ}/\text{kg}\cdot\text{K}]$	Temperature, T [$^{\circ}\text{C}$]
7	Wath_Ps	$P, s[\text{kJ}/\text{kg}\cdot\text{K}]$	Specific enthalpy, h [kJ/kg]
8	Wats_Ph	$P, h[\text{kJ}/\text{kg}]$	Specific entropy, s [$\text{kJ}/\text{kg}\cdot\text{K}$]

2.2.3. Functions for vapour-compression refrigerants (Ref)

This group of functions provides the thermo-physical properties for the 28 refrigerants listed in Table A2 of Appendix A. This group can also be divided into two subgroups; (a) for saturated refrigerants and (b) for superheated refrigerants.

a) Properties of saturated refrigerants

As for the water group, the functions for saturated refrigerants do not use mathematical formulae but store and interpolate the tabulated data provided by ASHRAE [2] by using a linear interpolation function. Table 2.6 lists 11 functions in this subgroup that determine the thermo-physical properties of saturated refrigerants at a given pressure and Table 2.7 lists 10 functions that determine the refrigerants properties at a given temperature.

Table 2.6. Properties of saturated refrigerants at a given pressure in kPa and quality

#	Function	Input	Output	Output unit
1	RefTsat_P	<i>Refrigerant name, P, x</i>	Saturation temperature, T_{sat}	[$^{\circ}\text{C}$]
2	Refv_Px	<i>Refrigerant name, P, x</i>	Specific volume, v	[m^3/kg]
3	Refu_Px	<i>Refrigerant name, P, x</i>	Specific internal energy, u	[kJ/kg]
4	Refh_Px	<i>Refrigerant name, P, x</i>	Specific enthalpy, h	[kJ/kg]
5	Refs_Px	<i>Refrigerant name, P, x</i>	Specific entropy, s	[$\text{kJ}/\text{kg}\cdot\text{K}$]
6	Refcp_Px	<i>Refrigerant name, P, x</i>	Specific heat, c_p	[$\text{kJ}/\text{kg}\cdot\text{K}$]
7	Refvs_Px	<i>Refrigerant name, P, x</i>	Velocity of sound	[m/s]
8	Refdv_Px	<i>Refrigerant name, P, x</i>	Dynamic viscosity, μ	[$\mu\text{Pa}\cdot\text{s}$]
9	Refk_Px	<i>Refrigerant name, P, x</i>	Thermal conductivity, k	[$\text{mW}/(\text{m}\cdot\text{K})$]
10	Refst_P	<i>Refrigerant name, P</i>	Surface tension	[mN/m]
11	RefTdew_P	<i>Refrigerant name, P</i>	Dew temperature	[$^{\circ}\text{C}$]

Table 2.7. Properties of saturated refrigerants at a given temperature in °C and quality

#	Function	Input	Output	Output unit
1	RefPsat_T	Refrigerant name, T, x	Saturation temperature, T_{sat}	[°C]
2	Refv_Tx	Refrigerant name, T, x	Specific volume, v	[m ³ /kg]
3	Refu_Tx	Refrigerant name, T, x	Specific internal energy, u	[kJ/kg]
4	Refh_Tx	Refrigerant name, T, x	Specific enthalpy, h	[kJ/kg]
5	Refs_Tx	Refrigerant name, T, x	Specific entropy, s	[kJ/kg.K]
6	Refcp_Tx	Refrigerant name, T, x	Specific heat, c_p	[kJ/kg.K]
7	Refvs_Tx	Refrigerant name, T, x	Velocity of sound	[m/s]
8	Refdv_Tx	Refrigerant name, T, x	Dynamic viscosity, μ	[μPa·s]
9	Refk_Tx	Refrigerant name, T, x	Thermal conductivity, k	[mW/(m·K)]
10	Refst_T	Refrigerant name, T	Surface tension	[mN/m]

Three of the 28 refrigerants are zeotropic blends, which are R404A, R407C, and R410A. For these three refrigerants, the saturation temperature means the bubble temperature, while the dew temperature is given by the last function shown on Table 2.6, **RefTdew_P**.

b) Properties of superheated refrigerants

Table 2.9 lists 8 functions that deal with superheated vapours of refrigerants. The first function in Table 2.9 applies the Redlich-Kwong (SRK) equation of state to determine the specific volume of superheated refrigerants. The following six functions apply Equations (B.18) to (B.23) given in Appendix B to determine the relevant property values. The last function (**Refs_Ph**) is an inversion function that uses an iterative solution to determine the fluid's entropy.

Table 2.9. Properties of superheated refrigerants given the pressure in kPa

#	Function	Input [unit]	Output [unit]
1	Refv_PT	Refrigerant name, P, T [°C]	v [m ³ /kg]
2	Refu_PT	Refrigerant name, P, T [°C]	u [kJ/kg]
3	Refh_PT	Refrigerant name, P, T [°C]	h [kJ/kg]
4	Refs_PT	Refrigerant name, P, T [°C]	s [kJ/kg.K]
5	RefT_Ph	Refrigerant name, P, h [kJ/kg]	T [°C]
6	RefT_Ps	Refrigerant name, P, s [kJ/kg.K]	T [°C]
7	Refh_Ps	Refrigerant name, P, s [kJ/kg.K]	h [kJ/kg]
8	Refs_Ph	Refrigerant name, P, h [kJ/kg]	s [kJ/kg.K]

It should be noted that the functions in this subgroup apply only for subcritical pressures. Appendix C verifies these functions for R134a by comparing their estimations with the data given by ASHRAE [2].

2.2.4. Functions for psychrometric analyses (Psy)

The functions of this group provide the thermodynamic properties of atmospheric air, which is a mixture of dry air and water-vapour. Appendix B shows the relations used for

the development of these functions which are those commonly used in psychrometric analyses. Table 2.10 lists 14 functions that are included in this group together with their input and output arguments. The letters in the function names have the following meanings: h (specific enthalpy), Db (dry bulb), Dp (dew point), P (pressure), Rh (relative humidity), Sh (specific humidity), v (specific volume), Wb (wet bulb). Case 6 in Table 2.1 shows how the function **PsyRh_PTSh** is used to determine the relative humidity for air given its pressure, temperature, and specific humidity.

Table 2.10. Functions for psychrometric analyses

#	Function	Input [unit]	Output [unit]
1	Psyv_PDbRh	P [kPa], T_{db} [°C], ϕ [%]	v [m ³ /kg]
2	PsyRh_PDbSh	P [kPa], T_{db} [°C], ω [kg/kg]	ϕ [%]
3	PsyRh_PDbWb	P [kPa], T_{db} [°C], T_{wb} [°C]	ϕ [%]
4	PsySh_PDbRh	P [kPa], T [°C], ϕ [%]	ω [kg/kg]
5	PsySh_PDbWb	P [kPa], T_{db} [°C], T_{wb} [°C]	ω [kg/kg]
6	Psyh_PDbSh	P [kPa], T [°C], ω [kg/kg]	h [kJ/kg]
7	Psyh_PDbRh	P [kPa], T [°C], ϕ [%]	h [kJ/kg]
8	PsyDp_PDbRh	P [kPa], T_{db} [°C], ϕ [%]	T_{dp} [°C]
9	PsyDp_PDbWb	P [kPa], T_{db} [°C], T_{wb} [°C]	T_{dp} [°C]
10	PsyDb_PRhSh	P [kPa], ϕ [%], ω [kg/kg]	T_{db} [°C]
11	PsyDb_PhSh	P [kPa], h [kJ/kg], ω [kg/kg]	T_{db} [°C]
12	PsyWb_PDbRh	P [kPa], T_{db} [°C], ϕ [%]	T_{wb} [°C]
13	PsyWb_PDbSh	P [kPa], T_{db} [°C], ω [kg/kg]	T_{wb} [°C]
14	PsyWb_PRhSh	P [kPa], ϕ [%], ω [kg/kg]	T_{wb} [°C]

2.2.5. Functions for absorption refrigeration solutions (LiB and NH3)

Thermax provides two groups of property functions for the analyses of vapour-absorption refrigeration systems: (a) water-lithium bromide (H₂O-LiBr) solution and (b) ammonia-water (NH₃-H₂O) solution. Each group has 13 property functions to determine properties of the relevant solution, but they use different formulae.

A. The H₂O-LiBr solution (LiB)

To determine the enthalpy (h), refrigerant temperature (T_r), and refrigerant concentration (X) of the H₂O-LiBr solution, these functions use the formulae given by ASHRAE [2] and to determine the entropy (s) and specific volume (v) the functions use the formulae given by Patek and Klomfar [4] and by Patterson and Perez-Blanco [5], respectively. This group needs two functions that determine the saturation pressure and saturation temperature of the refrigerant, which is water in this case. Although the two properties can be obtained by using the relevant functions in the water group, to make this group self-sufficient it has its own functions that determine these properties from the Antoine equations, which are Equations (B.16) and (B.17) given in Appendix B. Table 2.11 lists the 13 functions in the Lib-group.

Table 2.11. Functions for water-lithium bromide solution

#	Function	Input [unit]	Output [unit]
1	LiBh_TX	T [°C], X [%]	h [kJ/kg]
2	LiBv_TX	T [°C], X [%]	v [m ³ /kg]
3	LiBs_TX	T [°C], X [%]	s [kJ/kg.K]
4	LiBT_trX	Tr [°C], X [%]	T [°C]
5	LiBT_prX	Pr [kPa], X [%]	T [°C]
6	LiBT_hX	h [kJ/kg], X [%]	T [°C]
7	LiBTr_TX	T [°C], X [%]	Tr [°C]
8	LiBPr_TX	T [°C], X [%]	Pr [kPa]
9	LiBX_Ttr	T [°C], Tr [°C]	X [%]
10	LiBX_Tpr	T [°C], Pr [kPa]	X [%]
11	LiBT_sX	s [kJ/kg.K], X [%]	T [°C]
12	LiBpr_tr	T [°C]	P_{sat} [kPa]
13	LiBtr_tr	P [kPa]	T_{sat} [°C]

B. The ammonia-water solution (NH3)

To determine the enthalpy of the ammonia-water solution, this group applies the formulae given by Patek and Klomfar [6] and to determine the specific volume it applies that given by Sun [7]. The entropy of NH₃-H₂O solution in the liquid state (s_l) and the vapour state (s_v) are obtained by using the formulae given by El-Shaarawi et al [8]. The relations between refrigerant pressure and temperature of an ammonia-water solution with concentration are taken from Bourseau and Bugarel [9]. Table 2.12 lists the 13 functions in the NH₃-group.

Table 2.12. Functions for ammonia-water solution

#	Function	Input [unit]	Output [unit]
1	NH3h_TX	T [°C], X [%]	h [kJ/kg]
2	NH3v_TX	T [°C], X [%]	v [m ³ /kg]
3	NH3sl_prX	Pr [kPa], X [%]	s_l [kJ/kg.K]
4	NH3sv_prX	Pr [kPa], X [%]	s_v [kJ/kg.K]
5	NH3T_trX	Tr [°C], X [%]	T [°C]
6	NH3T_prX	Tr [°C], X [%]	T [°C]
7	NH3T_hX	h [kJ/kg], X [%]	T [°C]
8	NH3tr_TX	T [°C], X [%]	Tr [°C]
9	NH3pr_TX	T [°C], X [%]	Pr [kPa]
10	NH3X_Ttr	T [°C], Tr [°C]	X [%]
11	NH3X_Tpr	T [°C], Pr [kPa]	X [%]
12	NH3pr_tr	T [°C]	P_{sat} [kPa]
13	NH3tr_pr	P [kPa]	T_{sat} [°C]

The NH₃-group also needs two functions that determine the saturation pressure and saturation temperature of the refrigerant, which is ammonia. In order to make the group

self-sufficient, the group has its own functions that determine these properties instead of using the functions provided by the refrigerants group. Accordingly, the saturation pressure (P_{sat}) of ammonia is obtained from the following equation [7]:

$$P_{sat} = 10^3 \sum_{i=0}^6 a_i T^i \quad (2.1)$$

Where, T is in °C, P in kPa and values of the six coefficients a_1 to a_6 can be found in Sun [7]. The saturation temperature (T_{sat}) is obtained from Equation (2.1) by iteration.

2.2.6. Functions for combustion and chemical reactions (Chm)

The analyses of combustion and other chemical reactions involve mass and energy balances of the substances involved as reactants or products that can be solids, liquids, or gases. The gases involved are treated as ideal and, therefore, the group of functions for ideal gases “Gas” can be used here. However, combustion analyses require additional data like the heating value, enthalpy of formation, or Gibbs function. The group provided by Thermax for the analyses of combustion processes and chemical reactions consists of the three general functions shown in Table 2.13.

Table 2.13. Functions for thermodynamic properties of reacting systems

#	Function	Input argument	Output property
1	Chm_f1	Substance; property	$M, \bar{h}_f^0, \bar{g}_f^0, \bar{s}^0$
2	Chm_f2	Substance; property	$M, Q_H, Q_L, AF, Hv, \alpha, \beta, \gamma, \delta$
3	Chm_f3	Substance; property, temperature	$\bar{c}_p, \bar{h}, \bar{u}, \bar{s}^0$

All three functions require as input arguments the substance name and the name of the required property. In addition to those, the third function requires the temperature of the substance involved to be provided. The first function, **Chm_f1**, provides the molar mass (M), molar enthalpy of formation (\bar{h}_f^0), molar Gibbs function of formation (\bar{g}_f^0), and molar absolute entropy (\bar{s}^0) for the 29 reacting substances and reaction products that are listed in Table A.3 of Appendix A. Case 8 in Table 2.1 illustrates the use of this function.

The second function, **Chm_f2**, provides additional data needed for combustion analyses involving the 20 fuels and reacting substances listed in Table A.4. These include values of the molar mass (M), gravimetric higher and lower heating values (Q_H and Q_L), stoichiometric air-fuel ratio (AF_s) and heat of vaporisation (H_v). This function also provides the carbon, hydrogen, oxygen, and nitrogen contents of the substance ($\alpha, \beta, \gamma, \delta$) based on the general chemical representation $C_\alpha H_\beta O_\gamma N_\delta$. The third function, **Chm_f3**, determines four properties of ideal gases on a unit-mole basis. Case 9 in Table 2.1 shows the required input and the output of this function.

2.2.7. Functions for air at standard atmospheric pressure (Air)

This group provides the thermo-physical properties for air at standard atmospheric pressure as required by fluid-dynamics and heat-transfer analyses. Based on the tabulated data given by Cengel and Ghajar [10], the functions use a linear interpolation function to determine the air density (ρ), specific heat (c_p), thermal conductivity (k), thermal diffusivity (α), dynamic viscosity (μ), kinematic viscosity (ν) and Prandtl number (Pr) at temperatures in the range -150°C to 2000°C . Table 2.14 shows the names of the seven functions in this group with their corresponding output properties. Note that this group also provides a function for determining the specific-heat for air at constant pressure (c_p) which can be used instead of the function provided by the ideal-gas group.

Table 2.14. Properties of air at 1 atm pressure given the temperature in $^\circ\text{C}$

#	Function	Output	Output unit
1	Airrho_T	Density (ρ)	kg/m^3
2	Aircp_T	Specific heat (c_p)	$\text{J/Kg}\cdot^\circ\text{C}$
3	Airk_T	Thermal conductivity (k)	$\text{W/m}\cdot^\circ\text{C}$
4	Airdf_T	Thermal diffusivity (α)	m^2/s
5	Airdv_T	Dynamic viscosity (μ)	$\text{kg/m}\cdot\text{s}$
6	Airkv_T	Kinematic viscosity (ν)	m^2/s
7	AirPr_T	Prandtl number (Pr)	-

2.3. Using Thermax property functions in Excel formulae

Before Thermax functions can be used in Excel's formulae, you have to save it in your computer as an add-in. To do that, open the **Thermax** file and then save it in your computer as an "**Excel Add-in**". Excel comes with a number of add-ins that extend the application's functionality such as the Solver add-in. All add-ins are saved in one folder and active add-ins are automatically loaded when Excel starts up. In order to activate Thermax, open a new Excel sheet and then do the following:

1. Go to **File**, click **Options** and then select **Add-Ins**.
2. From the **Manage** ribbon at the bottom of the menu select **Excel Add-ins** and then press **Go**. The pull-down menu shown on Figure 2.2 will appear to you.
3. To add **Thermax** to the add-ins menu, tick (\checkmark) the corresponding box. If for any reason the add-in does not appear in the list, then click on **Browse** and search for it in the destination folder and select it.

The add-in functions can now be used in Excel's formulae just like its built-in functions. The following sections illustrate two methods for using these functions in Excel.

2.3.1. Accessing Thermax functions via the Function Wizard

This method suits the first-time users. To illustrate the method, let us start a formula by entering the equal sign (=) in any cell (say, cell B2). If you now press the fx button in the formula ribbon, the **Function Wizard** shown on Figure 2.3 will come up. The Function

Wizard firstly lists the various categories of built-in functions provided by Excel, e.g., financial, mathematical, statistical, etc. Scroll down the list of function categories and select the **User-defined** functions. Then, all the functions provided by Thermax will be listed alphabetically as shown on Figure 2.4.

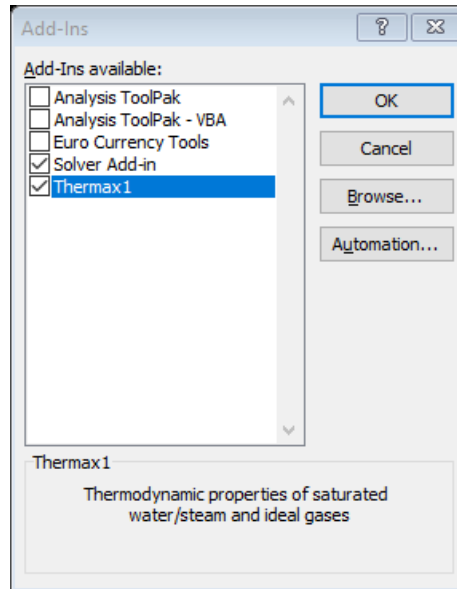


Figure 2.2. Adding Thermax to the menu of Excel add-ins

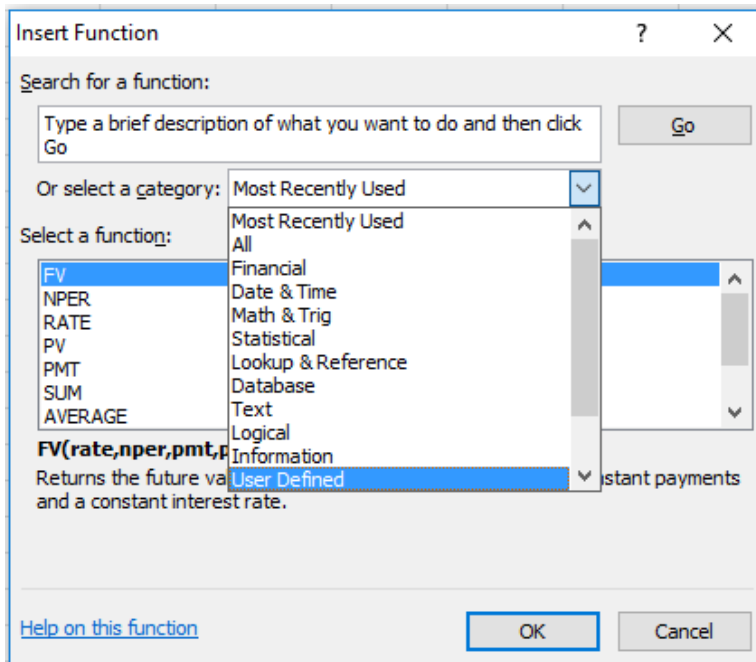


Figure 2.3. Finding the add-in user-defined functions in the Function Wizard

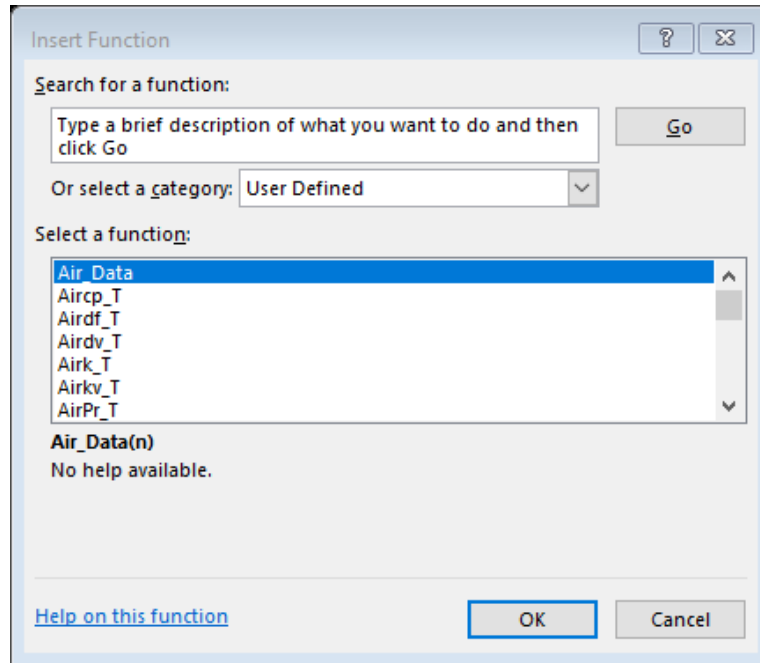


Figure 2.4. Thermax functions listed alphabetically in the User Defined category

The first function in the list of Figure 2.4, **Air_Data**, is an auxiliary function that stores the data for the seven thermophysical properties of air at standard atmospheric pressure. This function is called by other functions in the Air-group in order to determine the values of their respective properties at the required temperature. To start using the add-in functions, let us use it to determine the thermal conductivity (k) of air at 25°C. To do that, go down the list and select the function named **Airk_T**. Upon pressing the OK button, the **Function Arguments** box shown on Figure 2.5 will appear to you.

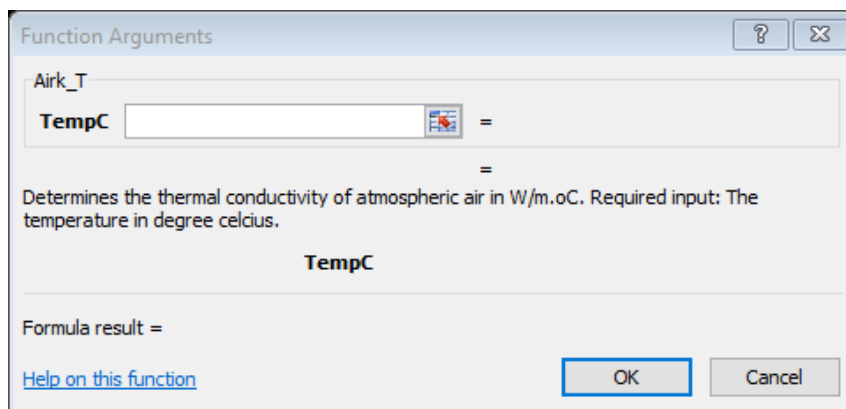


Figure 2.5. The Function Arguments box for the “Airk_T” function

Figure 2.5 shows that this function has one input parameter, which is the temperature in °C “TempC”, and gives a brief description of its intended use. Fill the form by entering

the given value of the temperature, 25, as shown on Figure 2.6. Note that the formula ribbon now shows the formula in cell B2, which is “=Airk_T(25)”. The form also shows the calculated value of k , which is 0.02551 W/m.°C. When you press the “OK” button, this value will appear in the cell B2. Check this value with the tabulated data.

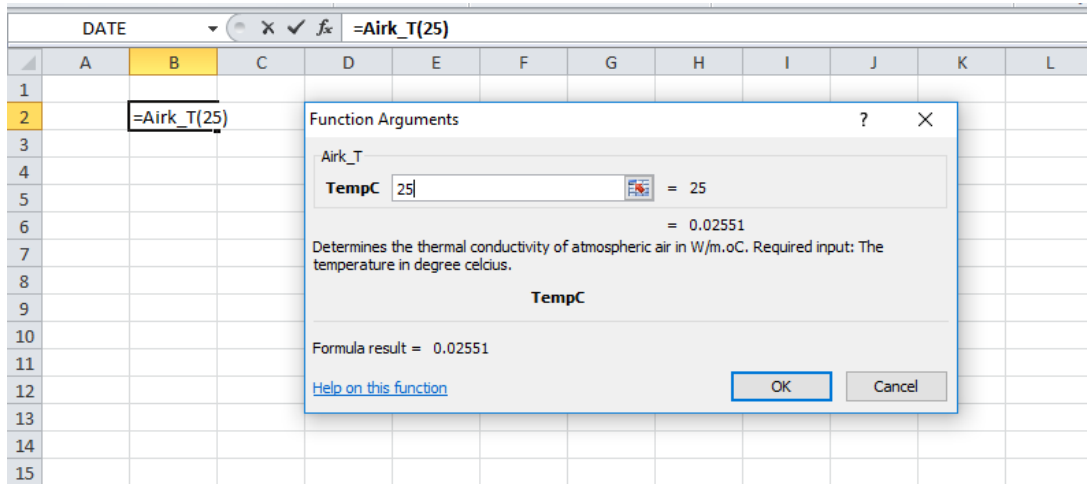


Figure 2.6. Using the function “Airk_T” to determine the thermal conductivity of atmospheric air at 25°C

2.3.2. Direct use of Thermax functions in Excel formulae

It is not necessary to follow the lengthy procedure described above by using the Function Wizard in order to use the add-in property functions. After some practice one can simply type in the formula that contains the property function in the required Excel cell. As mentioned earlier, the style adopted for naming Thermax functions makes it easy to identify the required function and the required input without having to memorise these for all the functions. For illustration, suppose that we want to determine the temperature of carbon-dioxide (CO₂) at which the value of its enthalpy (h) equals 750 kJ/kg. In this case, we need to use the function in the “Gas” group that determines the temperature for a given enthalpy value of the gas. Therefore, we start an Excel formula by typing the equal sign “=” in any cell and then type the prefix “Gas”. As shown on Figure 2.7, as soon as we type the prefix “Gas” after the equal sign, the user-interface will display all Thermax functions in the ideal-gases group for us to select from.

Since the property we want to find is the temperature, which the Gas-group functions require in absolute degree, we continue the name of the function by adding the letters “TK” immediately after the three-letter prefix “Gas” followed by an underscore. As shown on Figure 2.8, the user-interface then lists only the five functions in Table 2.2 that determine the gas temperature given h , P_r , s^0 , u , or v_r . To find the temperature from a known value of enthalpy, we have to select the “GasTK_h” function as shown on Figure 2.9. Excel will then ask you to enter the required input parameters. This function requires the name of the gas, which is “CO2”, and the value of enthalpy, which is 750 kJ/kg, as

shown on Figure 2.10. Press the “**Enter**” key, and the answer shown on Figure 2.11, which is 817.5544K, will be displayed.

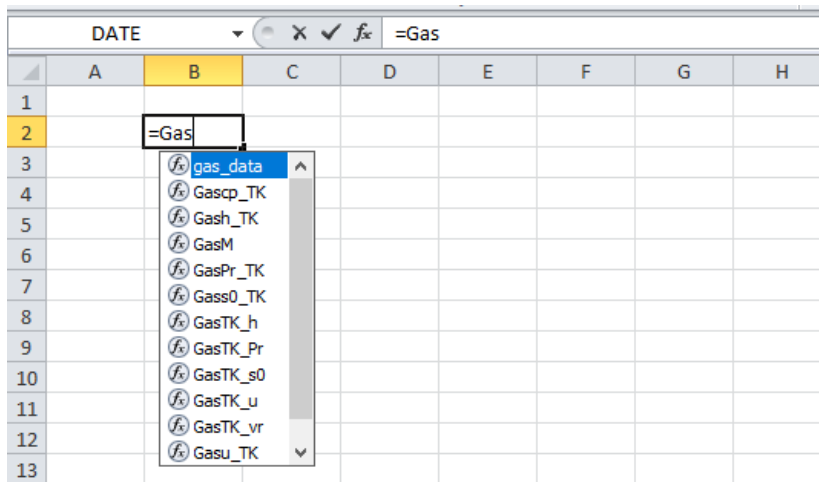


Figure 2.7. Excel UI showing all the functions in the Gas-group

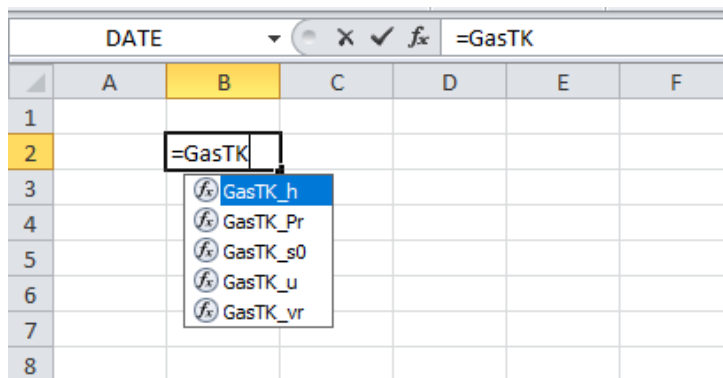


Figure 2.8. UI showing only the five functions that determine the temperature of an ideal gas from known values of h , p_r , s^0 , u , or v_r

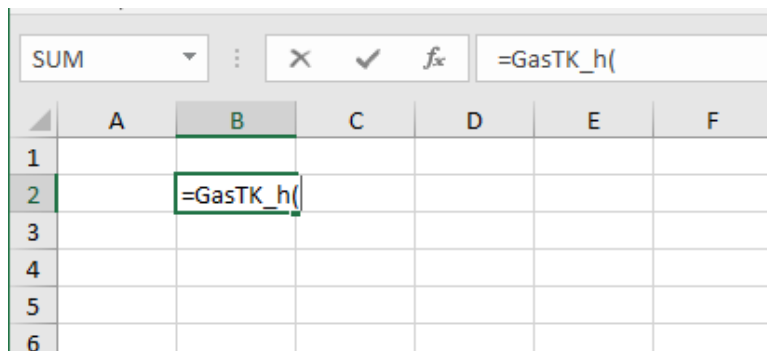


Figure 2.9. The required input for the GasTK_h function

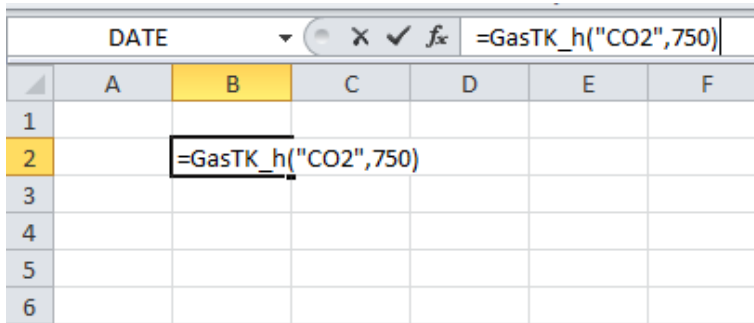


Figure 2.10. The required input for the GasTK_h function

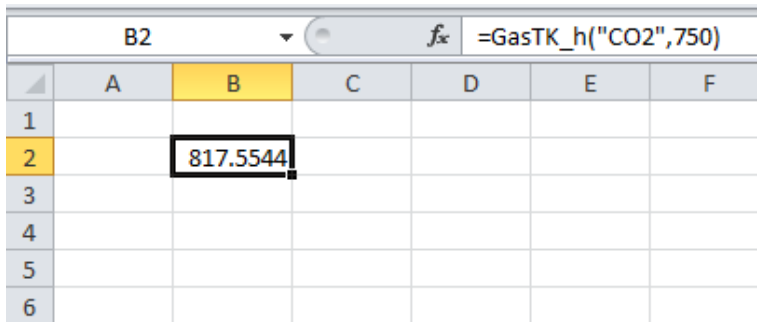


Figure 2.11. The temperature determined by the GasTK_h function

You can always call the **Function Wizard** if you are not certain about the required input parameters by pressing the *fx* button in the formula ribbon and the form shown on Figure 2.12 will appear to you. The form shows the two required input parameters for you to provide. Pressing the “Enter” key or the “OK” button after entering the required data, the function will calculate the corresponding temperature which is 817.5544K as shown on Figure 2.11. This value can be checked by comparison with the tabulated data.

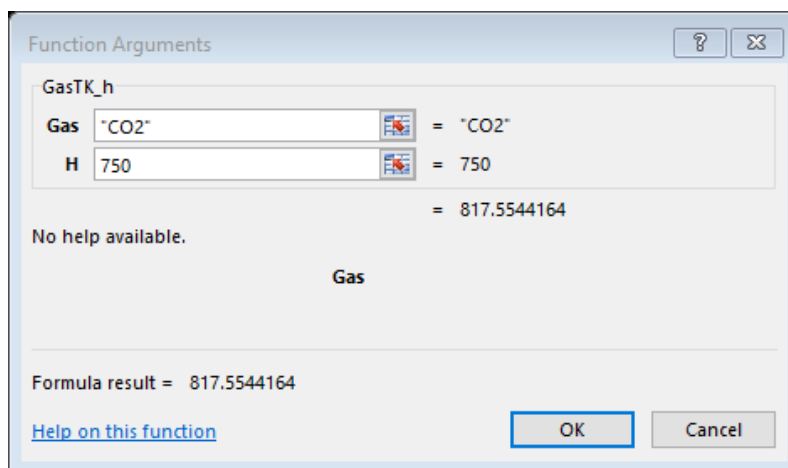


Figure 2.12. The Function Wizard with the required input for the GasTK_h function

2.4. Thermodynamic analysis using Thermax functions

This section shows how Thermax functions can be used in thermodynamic analyses with Excel. The case considered uses the functions in the Gas-group for applying the variable specific-heat method (the exact method) in thermodynamic analyses.

Example 2.1. Thermodynamic analysis with the exact method

Figure 2.13 shows a well-insulated piston–cylinder device that initially contains 0.1 m³ of air at 100 kPa, 330K. Fifty kJ of heat is transferred to the air causing the air to expand at constant pressure. Treating air as an ideal gas, determine the final temperature inside the cylinder using: (a) the approximate constant-specific heat method, with $c_p = 1.005$ kJ/kg.K, and (b) the exact variable specific-heat method with Thermax functions.

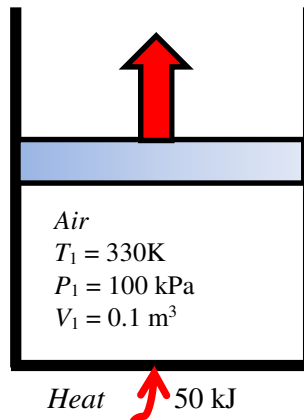


Figure 2.13. Schematic for Example 2.1

(a) Solution with the approximate method

Using the approximate constant specific heat method, the final temperature is determined from:

$$T_2 = T_1 + \frac{Q}{m \times c_p} \quad (2.2)$$

Where m is the mass of air in the piston-cylinder device, c_p is the average value of the specific heat at constant pressure, and Q is the amount of heat added. The mass of air is first calculated from the ideal-gas law:

$$m = \frac{P_1 V_1}{R \times T_1} \quad (2.3)$$

Where R is the gas constant for air, $R = 0.287$ kJ/kg.K. Substituting for P_1 , V_1 , R and T_1 in Equation (2.3), leads to $m = 0.105585$ kg and substituting for m in Equation (2.2) gives $T_2 = 801.194\text{K}$.

(b) Solution with the exact method

To apply the exact method by using Thermax functions, we have to determine the final enthalpy, h_2 . From the first law of thermodynamics applied to the closed system that undergoes a constant-pressure process, h_2 is given by:

$$h_2 = h_1 + Q / m \quad (2.4)$$

Once h_2 is found, the final temperature, T_2 , can be determined by using the function **GasTK_h** in the Gas-group. Figure 2.14 shows the Excel sheet developed for this example. The given data are inserted at the left-hand side of the sheet together with the gas constant ($R_$) and specific heat (cp) for air.

H8		fx =(T_2approx-T_2exact)/T_2exact*100									
	A	B	C	D	E	F	G	H	I	J	K
1				Approximate method			Exact method				
2	T_1	330	K	m	0.106	=P_1*V_1/(R_*T_1)	h_1	330.027	=Gash_TK("Air",T_1)		
3	P_1	100	kPa								
4	V_1	0.1	m3	T_2approx	801.194	=T_1+Q/(m*cp)	h_2	803.577	=h_1+Q/m		
5											
6	Q	50	kJ				T_2exact	781.644	=GasTK_h("Air",h_2)		
7											
8	R_	0.287	kJ/kg.K				Error	2.501	= (T_2approx-T_2exact)/T_2exact*100		
9	cp	1.005	kJ/kg.K								
10											

Figure 2.14. Excel sheet developed for Example 2.1

The calculations part is divided into two parts that determine the final temperature according to the approximate method and the exact method using the corresponding equations given above. Figure 2.14 also reveals the formulae used in these calculations. Note that “cell-labelling” has been used in the Excel formulae. As the figure shows, the answer found by the exact method for T_2 is 781.6K, while the approximate method determines the final temperature as 801.2K. In this case, the approximate constant specific-heat method results in an error of 2.5%.

2.5. Closure

This chapter introduces the Thermax add-in and its seven groups of property functions that determine the thermo-physical properties of various types of working fluids including 29 ideal gases, saturated water and superheated steam, 28 refrigerants, humid air for psychrometric analyses, two aqua solutions for vapour-absorption refrigeration, reacting substances, and air at atmospheric pressure. Thermax property functions are named in a way that helps the user to find the appropriate function via Excel’s user-interface and function wizard. The chapter shows how the functions can be used in Excel formulae and illustrates the use of the ideal-gas functions for thermodynamic analyses with the exact variable specific-heat method. There are a number of auxiliary functions that are provided by the add-in its groups but do not appear in the respective tables some of which are mentioned in the following chapters where they are used.

Thermax property functions for ideal-gases, superheated steam, atmospheric humidified air, the two vapour-absorption fluids, and combustion gases use verified equations for these substances [1,3-9]. The functions for saturated water and saturated refrigerants determine the properties by interpolation of the verified data provided by ASHRAE [2]. The functions for atmospheric air at standard pressure also use interpolation of published data [10]. The only group of functions that use equations modified by the author are those developed for superheated refrigerants. The verification of these functions is discussed in Appendix C and a paper published by the author and co-workers [11]. The following six chapters illustrate the use of the various add-in functions for thermodynamic analyses of gas power generation cycles, vapour-power cycles, vapour-compressions refrigeration cycles, air-conditioning processes, combustion processes, and vapour-absorption cycles. The last two chapters of the book illustrate the use of the add-in function for thermo-economic optimisation analyses of energy-conversion systems.

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Refrigerants, Proceedings of the 1st National Conference on Applied Science, Engineering & Technology 2019, CASET – 2K19, 11th June 2019, Ibri, Oman

Exercises

- Complete the following table by specifying the usage of the given Thermax function according to its name:

#	Function	Output property	Input /properties
1	Gascp_TK("CO2",300)		
2	WatTsat_P(200)		
3	WatT_Ph(200, 3487.7)		
4	RefPsat_T("R134a",0.0)		
5	PsyTs_P(100)		
6	Nh3Pr_TX(200,80)		
7	Airdv_T(500)		
8	Chm_f2("HDL","QL")		

- Name the appropriate Thermax functions that determine the following properties:

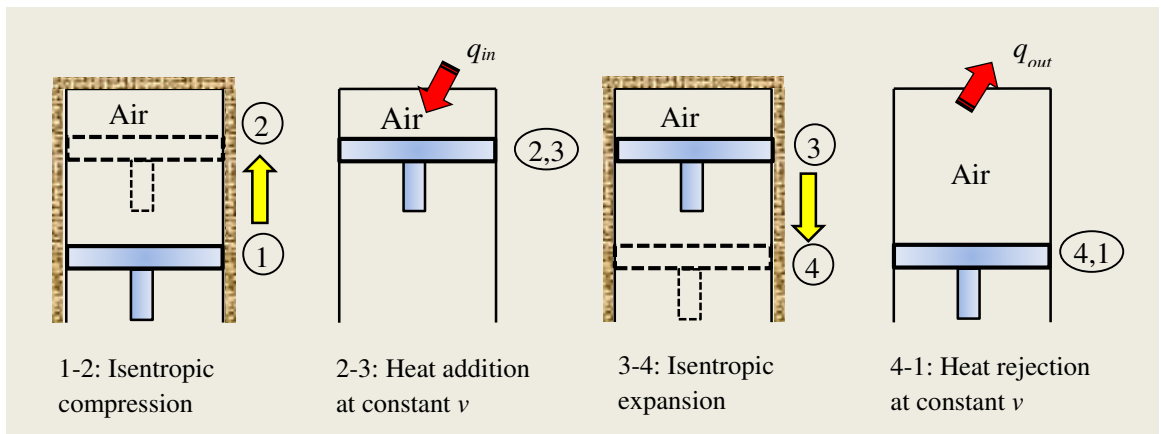
#	Task	Thermax function
1	The enthalpy of saturated liquid water at 25°C	
2	The internal energy of oxygen at 300K	
3	The entropy of superheated steam at 10 kPa, 200°C	
4	The absolute temperature at which the relative pressure of air is equal to 15	
5	The saturation pressure for R-134a at -15°C	
6	The dry-bulb temperature of humid air at $P = 101$ kPa, $\phi = 50\%$, $\omega = 0.01$	
7	The enthalpy of ammonia-water solution at 30°C, $X= 50\%$	
8	The higher heating value for gasoline	

- Using Thermax functions, determine the values of the following fluid properties:

#	Fluid	Given properties	Required property	Value
1	Saturated water	100 kPa, $x = 0.5$	Enthalpy (h)	
2	Air	700K	Relative volume (v_r)	
3	Steam	100°C, $x = 1.0$	Entropy (s)	
4	CO ₂	450K	Specific heat (c_p)	
5	Hydrogen	$h = 2000$ kJ/kg	Temperature (T)	

Chapter 3

Analyses of gas power cycles



This chapter illustrates the use of Thermax functions for analysing two important gas power cycles, which are the Brayton cycle for gas turbine and the Otto cycle for spark-ignition internal-combustion engines. For the Brayton cycle both the simple and the regenerative cycles are analysed and for the Otto cycle both energy and exergy analyses are presented. Values of the key parameters of the cycles determined by using Thermax functions are verified against the relevant values given in standard thermodynamics textbooks. The results obtained for the simple Brayton cycle and the Otto cycle are also compared with those obtained by using the “Ideal-Gas” add-in [1].

3.1. The ideal Brayton cycle

The Brayton cycle is the ideal cycle for gas-turbines. Unlike the real gas-turbine cycle, it is a closed cycle with a constant mass of the working fluid going through the system’s components as shown on Figure 3.1. The cycle consists of four processes; compression in an ideal gas compressor, heat-addition from a high-temperature source, expansion in an ideal gas turbine, and heat-rejection to a low-temperature sink. Figure 3.2 shows the Brayton cycle on a T - s diagram.

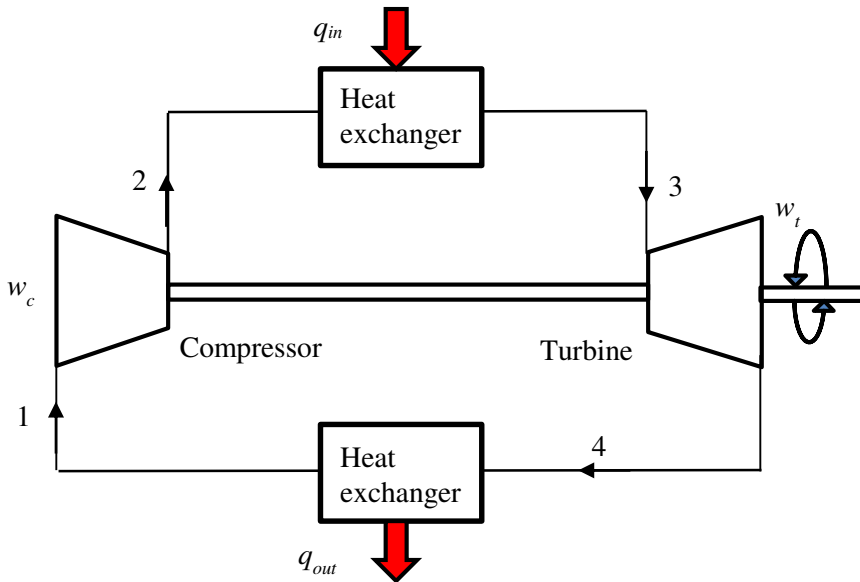


Figure 3.1. Schematic diagram of the closed-cycle gas-turbine

Although the working fluid in the closed cycle can be any suitable gas, in the following analysis it is assumed to be air. Referring to Figure 3.2, the compressor work (w_c) and turbine work (w_t), per unit mass flow rate of the air, are determined from:

$$w_c = (h_2 - h_1) \quad (3.1)$$

$$w_t = (h_3 - h_4) \quad (3.2)$$

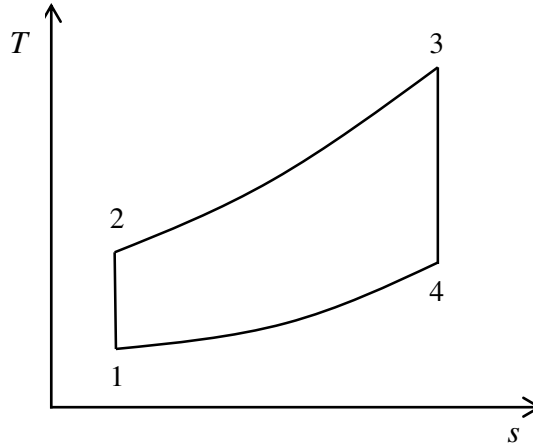


Figure 3.2. T - s diagram for the ideal Brayton cycle

Where h_1 , h_2 , h_3 , and h_4 are values of the enthalpy at states, 1, 2, 3, and 4, respectively. The amount of heat addition (q_{in}) per unit mass flow of the air is given by:

$$q_{in} = (h_3 - h_2) \quad (3.3)$$

Therefore, the net work (w_{net}), back-work ratio (BWR), and thermal efficiency (η) of the cycle are determined from:

$$w_{net} = w_t - w_c \quad (3.4)$$

$$BWR = w_c / w_t \quad (3.5)$$

$$\eta = w_{net} / q_{in} \quad (3.6)$$

Given the compressor's inlet temperature, T_1 , and the turbine's inlet temperature, T_3 , the discharge temperature from the compressor (T_2) and the discharge temperature from the turbine (T_4) are determined by using the variable specific-heat method of analysis from the corresponding relative pressures P_{r2} and P_{r4} given by:

$$P_{r2} = P_{r1} \times \frac{P_2}{P_1} \quad (3.7)$$

$$P_{r4} = P_{r3} \times \frac{P_4}{P_3} \quad (3.8)$$

Where P_{r1} and P_{r2} are the relative pressures at states 1 and 2, respectively. For the ideal cycle without pressure losses, $P_3 = P_2$ and $P_4 = P_1$. The following example illustrates the procedure for using Thermo property functions for analysing the cycle with Excel. The example is based on Example 9.5 in Cengel and Boles [2].

Example 3.1. Analysis of the simple ideal Brayton cycle

A gas-turbine power plant that operates on an ideal Brayton cycle with air as the working fluid has a pressure ratio of 8. The gas temperature at the compressor inlet is 300 K and at the turbine inlet is 1300 K. Determine (a) the net work per unit mass flow rate of the working fluid, (b) the back work ratio, and (c) the thermal efficiency.

Solution

Figure 3.3 shows the Excel sheet developed for this example using Thermo functions. The figure shows the general layout adopted in this book for sheet arrangement according to which the sheet is divided from left to right into three main parts: (i) Input data, (ii) Intermediate calculations, and (iii) Final results. In the present case, the input data include the given values of the two temperature values at states 1 and 3 (T_1 and T_3) and the pressure ratio (rp). The middle part of the sheet, which is reserved for the calculation of intermediate results, shows the calculated values of the two unknown temperatures T_2 and T_4 and the enthalpy values at the four states in the cycle. The final results are the compressor work (w_c), the turbine work (w_t), the heat input (Q_{in}), the back work ratio (BWR), and thermal efficiency (η) as shown on the right side of the sheet.

η		fx =(w_t-w_c)/q_in									
A	B	C	D	E	F	G	H	I	J	K	L
1	Input Data		Intermediate calculations						Final results		
2	T_1	300 K	Pr_2	11.06829198		h_1	299.8455		w_c	243.6869	
3											
4	rp	8	T_2	538.1465495		h_2	543.5324		w_t	606.014	
5											
6	T_3	1300 K	Pr_4	41.69167583		h_3	1396.057		q_in	852.5248	
7											
8			T_4	769.2393498		h_4	790.0433		BWR	0.402114	
9											
10									η	0.425005	
11											

Figure 3.3. The Excel sheet developed for Example 3.1

Figure 3.4 shows the formula entered in each cell of the calculations part using Thermo functions. Note that “cell-labelling” has been used in the formulae. Only three Thermo functions from the Gas-group have been used in the Excel model with air as the gas which are: **GasPr_TK**, **GasTK_Pr**, and **Gash_TK**. For the purpose of comparison, a similar Excel sheet was developed by using the IdealGas add-in developed at the University of Alabama [1]. Figure 3.5 shows the Excel sheet and Figure 3.6 reveals the function used in it. Note that the IdealGas functions have the advantage of allowing two systems of

units to be used, but they can only be used for air. By comparison, Thermo functions only use the “SI” system but they can be used for different gases.

✓ fx $= (w_t - w_c) / q_{in}$					
D	E	F	G	H	
Intermediate calculations					
Pr_2	=GasPr_TK("Air",T_1)*rp		h_1	=Gash_TK("Air",T_1)	
T_2	=GasTK_Pr("Air",Pr_2)		h_2	=Gash_TK("Air",T_2)	
Pr_4	=GasPr_TK("Air",T_3)/rp		h_3	=Gash_TK("Air",T_3)	
T_4	=GasTK_Pr("Air",Pr_4)		h_4	=Gash_TK("Air",T_4)	

Figure 3.4. Thermo functions used in the Excel sheet of Example 3.1

η											fx $= (w_t - w_c) / q_{in}$	
	A	B	C	D	E	F	G	H	I	J	K	
1	Input Data			Intermediate calculations				Final results				
2	T_1	300	K	Pr_2	11.01667122		h_1	299.6384		w_c	243.6869	
3												
4	rp	8		T_2	538.1465495		h_2	543.3253		w_t	606.014	
5												
6	T_3	1300	K	Pr_4	41.49723248		h_3	1395.85		q_in	852.5248	
7												
8				T_4	769.2393498		h_4	789.8362		BWR	0.402114	
9												
10										η	0.425005	
11												

Figure 3.5. Excel sheet for Example 3.1 using the IdealGas add-in

fx $= (w_t - w_c) / q_{in}$					
C	D	E	F	G	H
Intermediate calculations					
	Pr_2	=Prel_air(T_1,"si")*rp		h_1	=h_air(T_1,"si")
	T_2	=T_Prel_air(Pr_2,"si")		h_2	=h_air(T_2,"si")
	Pr_4	=Prel_air(T_3,"si")/rp		h_3	=h_air(T_3,"si")
	T_4	=T_Prel_air(Pr_4,"si")		h_4	=h_air(T_4,"si")

Figure 3.6. IdealGas functions used in the Excel sheet of Example 3.1

Table 3.1 shows the values determined by the two property add-ins for the key cycle parameters and their corresponding values given by Cengel and Boles [2]. The figure of

the table shows only minor differences between the values obtained by the property add-ins and those given by Cengel and Boles [2].

Table 3.1. Verification of the two add-ins' results with those of Cengel and Boles [2]

Parameter	Cengel and Boles [2]	Thermax	IdealGas
w_c	244.16	243.69	243.69
w_t	606.60	606.01	606.01
q_{in}	851.62	852.52	852.52
BWR	0.403	0.402	0.402
η	0.426	0.425	0.425

3.2. The regenerative Brayton Cycle

Gas turbines can sustain higher combustion temperatures than those typically met in internal-combustion engines, but the high combustion temperatures lead to high exhaust temperatures as well. By adding a regenerator to the simple gas-turbine system, as shown on Figure 3.7, the energy in the hot exhaust gases that can reach more than 500°C is utilised to preheat the compressed air before it goes to the combustion chamber; a process called *regeneration*. Regeneration reduces the fuel combustion and improves the plant's thermal efficiency, but the cost of the heat-exchanger increases that of the modified system. The economic benefit due to regeneration depends not only on the cost of the heat-exchanger, but also on the system's pressure ratio. While the cost of the heat-exchanger depends on its size and effectiveness, there is a certain value for the pressure ratio that maximises the system's thermal efficiency.

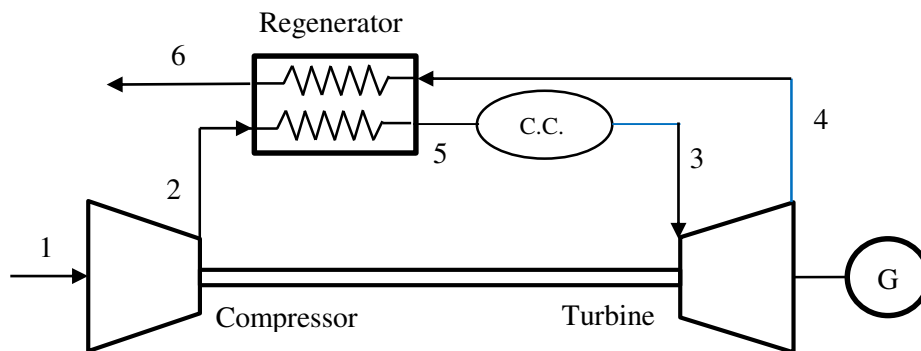


Figure 3.7. Schematic diagram of the regenerative gas-turbine

Figure 3.8 shows the T - s diagram for the regenerative Brayton cycle assuming zero pressure losses in the combustion chamber and heat-exchanger. Due to friction losses in both compressor and turbine, the actual exit temperatures from these devices (i.e., T_2 and T_4) are different from the ideal values obtainable by the isentropic compression and expansion processes (T_{2s} and T_{4s}).

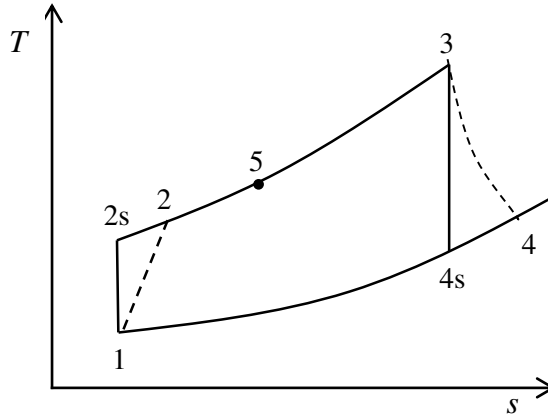


Figure 3.8. T - s diagram for the regenerative Brayton cycle

As for the simple Brayton cycle considered earlier, the thermal efficiency (η) is given by:

$$\eta = w_{net} / q_{in} \quad (3.9)$$

Where, w_{net} is the net output work from the plant and q_{in} is its heat input. The net output work for the gas-turbine power plant is the difference between the turbine work output (w_t) and the compressor work input (w_c). Using the numbering scheme of Figures 3.7 and 3.8 to indicate the state of the working fluid entering and leaving the compressor and turbine, the net output work in terms of fluid enthalpies is given by:

$$w_{net} = (h_3 - h_4) - (h_2 - h_1) \quad (3.10)$$

The heat input to the power plant is given by the difference in enthalpies of the combustion gases and the preheated air entering the combustion chamber, i.e.:

$$q_{in} = (h_3 - h_5) \quad (3.11)$$

Given the temperature and pressure of air at the compressor inlet, the ideal relative pressure after the compressor ($P_{r,2s}$) is determined from [2]:

$$P_{r,2s} = P_{r1} \frac{P_2}{P_1} = P_{r1} \cdot r_p \quad (3.12)$$

Where, r_p stands for the pressure ratio. $P_{r,2s}$ is then used to find T_{2s} , which is the temperature after an ideal isentropic compression process. Once T_{2s} is found, h_{2s} can be determined by using the property function. The actual enthalpy (h_2) is then found from:

$$h_2 = h_1 + (h_{2s} - h_1) / \eta_c \quad (3.13)$$

Where, η_c is the compressor's isentropic efficiency. Similarly, the relative pressure after the expansion process ($P_{r,4s}$) is determined from:

$$P_{r,4s} = P_{r3} \frac{P_4}{P_3} = P_{r3} / r_p \quad (3.14)$$

$P_{r,4s}$ is then used to find the temperature after an ideal expansion process T_{4s} , from which h_{4s} can be determined. The actual enthalpy (h_4) is then found from:

$$h_4 = h_3 - (h_3 - h_{4s}) \times \eta_t \quad (3.15)$$

Where, η_t is the turbine's isentropic efficiency. The temperature of the compressed air entering the combustion chamber (T_5) and, therefore, the saving in fuel consumption, depends on the effectiveness of the regenerator (ε) which is defined as:

$$\varepsilon = (T_5 - T_2) / (T_4 - T_2) \quad (3.16)$$

Given an estimate for ε , Equation (3.16) can be rearranged to get:

$$T_5 = T_2 + \varepsilon(T_4 - T_2) \quad (3.17)$$

Example 3.2. Analysis of the regenerative Brayton cycle

A gas-turbine power plant operates on a regenerative Brayton cycle with air entering the compressor at 100 kPa, 300 K. Combustion gases leave the combustion chamber at 1400 K. The regenerator effectiveness is 80% and the isentropic efficiency of both the compressor and the turbine is 80%. Determine the pressure ratio that yields the maximum net work output and the maximum thermal efficiency of the plant.

Solution

Figure 3.9 shows the Excel sheet prepared for this example using Thermax functions. The input data shown in the left-side of the sheet includes the air intake temperature (T_1) and pressure (P_1), the pressure ratio (Pratio), and the combustion temperature (T_3). The data part also includes the isentropic efficiency of the compressor (Eff_c), the isentropic efficiency of the turbine (Eff_t), and the regenerator effectiveness (Eff_regen). The middle part of the sheet shows the calculated values of T_2 and T_4 . The figure shows the enthalpy values as obtained by using Thermax functions. The formula used in each cell is inserted next to it. The right-side of the sheet shows the main results, which include values of the input compression work, the output expansion work, the net work output, the heat input, and the thermal efficiency.

	B	C	D	E	F	G	H	I	J	K	L
1											
2	T ₁	300		h ₁	299.8455	=Gash_TK("air",T_1)		h ₅	890.2033	=h_2+Eff_regen*(h_4-h_2)	
3	P ₁	100		Pr ₁	1.383536	=GasPr_TK("air",T_1)					
4	Pratio	10		Pr _{2s}	13.83536	=Pr_1*Pratio		w _c	349.0347	=(h_2-h_1)	
5	T ₃	1400		T _{2s}	572.0764	=GasTK_Pr("air",Pr_2s)		w _t	565.2241	=(h_3-h_4)	
6	Eff _c	0.8		h _{2s}	579.0732	=Gash_TK("air",T_2s)		w _{net}	216.1894	=w_t-w_c	
7	Eff _t	0.8		h ₂	648.8802	=h_1+(h_2s-h_1)/Eff_c		Q _{in}	625.5549	=(h_3-h_5)	
8	Eff _{regen}	0.8		T ₂	638.1146	=GasTK_h("air",h_2)		η	0.345596	=(w_t-w_c)/Q_in	
9											
10				h ₃	1515.758	=Gash_TK("air",T_3)					
11				Pr ₃	454.3223	=GasPr_TK("air",T_3)					
12				Pr _{4s}	45.43223	=Pr_3/Pratio					
13				T _{4s}	786.8156	=GasTK_Pr("air",Pr_4s)					
14				h _{4s}	809.2281	=Gash_TK("air",T_4s)					
15				h ₄	950.5341	=h_3-(h_3-h_4s)*Eff_t					
16				T ₄	914.5512	=GasTK_h("air",h_4)					
17											

Figure 3.9. The Excel sheet developed for the regenerative Brayton cycle

The sheet shows the results at a pressure ratio of 10 at which the corresponding values of the net output work and thermal efficiency are 216.19 kJ/kg and 0.346, respectively. The value of the pressure-ratio (Pratio) in cell C4 was changed from 2 to 16 and Figure 3.10 shows the calculated values for the net specific work and thermal efficiency plotted against the pressure ratio. The figure shows that the net output work and thermal efficiency reach their maximum values at different pressure ratios. While the maximum net work output occurs at a pressure ratio of about 8, the maximum thermal efficiency occurs much earlier at a pressure ratio of about 5 or less. Note that exact values of the intermediate pressure that maximise the net work or thermal efficiency of the cycle can be determined by using the Solver add-in (refer to Exercise 1).

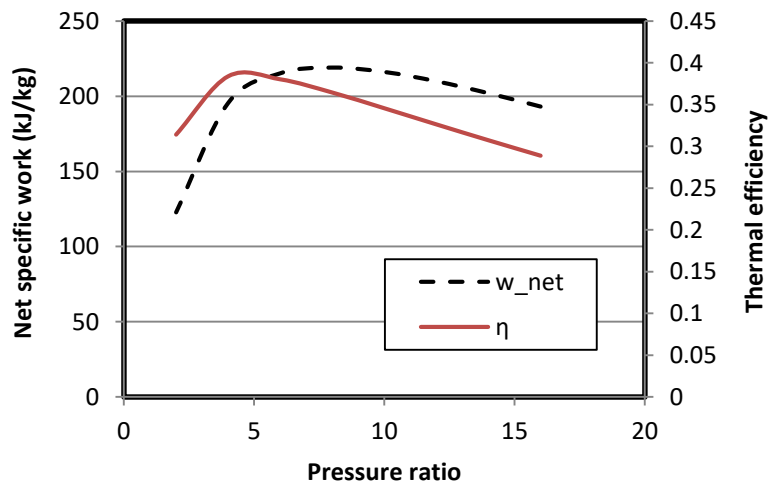


Figure 3.10. Variation of the net specific work and thermal efficiency of the regenerative Brayton cycle with the turbine's pressure ratio

3.3. Energy analysis of the Otto cycle

The Otto cycle and the Diesel cycle are two ideal cycles used for modelling the cycles in internal combustion (I.C.) engines. The Otto cycle is used for modelling spark-ignition I.C. engines, while the Diesel cycle is used for modelling compression-ignition I.C. engines. Both cycles adopt “air-standard” assumptions according to which the working fluid is considered to be air which is treated as an ideal gas. Figure 3.11 shows the four processes that constitute the Otto cycle:

Process 1-2: Adiabatic and reversible compression of air

Process 2-3: Constant-volume heat addition

Process 3-4: Adiabatic and reversible expansion of air

Process 4-1: Constant-volume heat rejection

The P - v diagram of the Otto cycle is shown on Figure 3.12. Processes 1-2 and 3-4 are isentropic processes because they are both assumed to be adiabatic and reversible.

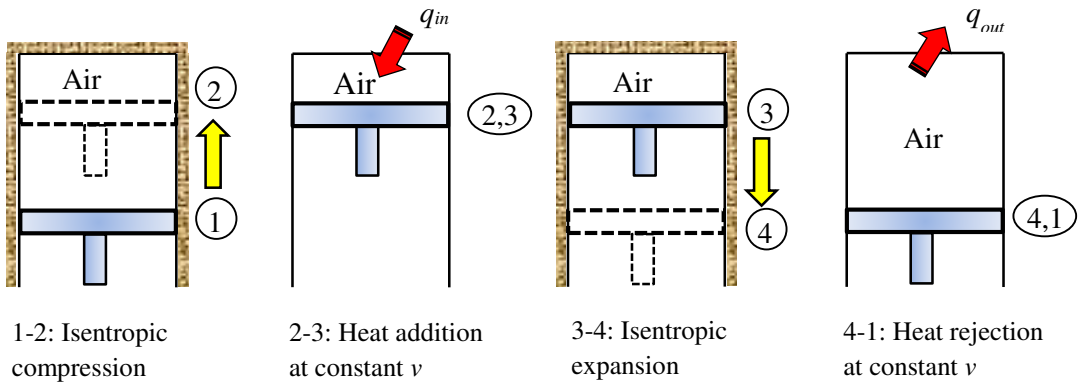


Figure 3.11. The Otto cycle (Adapted from Cengel and Boles [2])

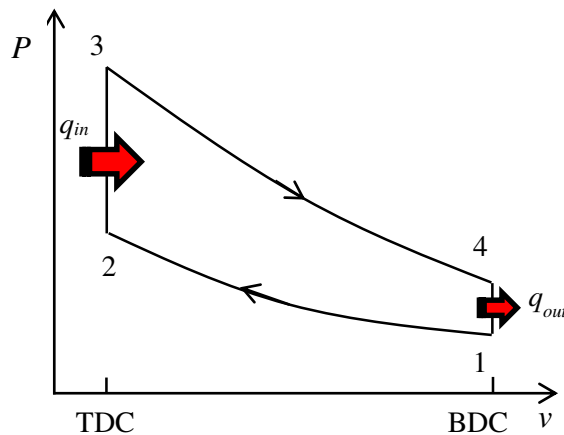


Figure 3.12. P - v diagram of the Otto cycle (Adapted from Cengel and Boles [2])

The analytical model

The analysis of a cycle that aims to determine its thermal efficiency is called an “energy analysis”. For the ideal Otto-cycle shown on Figure 3.12, we have [3]:

$$v_1 = RT_1 / P_1 \quad (3.18)$$

$$v_2 = v_1 / r \quad (3.19)$$

$$v_3 = v_2 \quad (3.20)$$

$$v_4 = v_1 \quad (3.21)$$

Where, R is the gas constant (for air $R= 0.287$ kJ/kg.K) and r is the compression ratio of the cycle (for modern spark-ignition engines $8 \leq r \leq 11$). Applying the variable specific heat method for or the isentropic compression and expansion processes:

$$\frac{v_{r2}}{v_{r1}} = \frac{v_2}{v_1} = 1/r \quad (3.22)$$

$$\frac{v_{r4}}{v_{r3}} = \frac{v_4}{v_3} = r \quad (3.23)$$

Where, v_r is the relative specific volume. The last two relationships can be used to determine the two temperatures after the compression and expansion processes. The amount of heat added in process 2-3 per kg of the working fluid (q_{in}) is calculated from:

$$q_{in} = (u_3 - u_2) \quad (3.24)$$

The amount of heat removed per kg of the working fluid (q_{out}) is calculated from:

$$q_{out} = (u_4 - u_1) \quad (3.25)$$

Applying the first-law of thermodynamics, the net work from the cycle is given by:

$$w_{net} = q_{in} - q_{out} \quad (3.26)$$

Therefore, the thermal efficiency of the Ott cycle (η_{Otto}) is given by:

$$\eta_{Otto} = \frac{w_{net}}{q_{in}} \quad (3.27)$$

The cycle's mean-effective pressure (MEP) is defined as:

$$MEP = \frac{W_{net}}{v_{max} - v_{min}} = \frac{W_{net}}{v_1 - v_2} \tag{3.28}$$

Although the above analytical model is based on the usual air-standard assumptions, by adopting the variable specific-heat method it yields more realistic results than those obtainable by adopting the approximate constant specific heat method (refer to Example 2.1). The following example shows how the property functions provided by Thermax and IdealGas [1] can be used to be used for its application.

Example 3.3. Energy analysis of the Otto cycle

An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 100 kPa and 17°C. During the constant-volume heat-addition process, 800 kJ/kg of heat is transferred to air. Accounting for the variation of specific heats of air with temperature, conduct an energy analysis of the cycle to determine:

- (i) the net work output and thermal efficiency,
- (ii) the mean effective pressure for the cycle.

This example is based on Examples 9-2 in Cengel and Boles [2].

Solution

Figures 3.13 and 3.14 show the Excel sheets developed for analysing the Otto cycle by using property functions for ideal gases provided by Thermax and IdealGAs, respectively. The sheets show the formulae used in the calculation parts and the formula window in each sheet reveals the formula used for calculating the mean effective pressure according to Equation (3.28). Since the IdealGas add-in does not provide a function for determining the gas temperature from its internal energy, the temperature T_3 on Figure 3.14 has been found by using the Goal-Seek command of Excel. Table 3.2 compares the values obtained by the two add-ins to those given by Cengel and Boles [2]. The figures in the table show good agreement between the three solutions.

MEP		=w_net/(v_1-v_2)									
B	C	D	E	F	G	H	I	J	K	L	
1 Energy analysis											
2	rc	8	v_1	0.8323	=R_air*T_1/P_1	u_3	1273.92	=u_2+Q_in	q_out	381.912	
3	T_1	290 K	u_1	206.516	=gasu_TK("air",T_1)	T_3	1572.59	=gasTK_u("air",u_3)			
4	P_1	100 kPa	vr_1	676.064	=gasvr_TK("air",T_1)	P_3	4338.19	=(T_3/T_2)*P_2	w_net	418.088	
5	Q_in	800 kJ/kg	vr_2	84.508	=vr_1/rc	vr_3	6.06462	=gasvr_TK("air",T_3)			
6			T_2	648.727	=GasTK_vr("air",vr_2)	vr_4	48.5169	=vr_3*rc	η_1	0.52261	
7	R_air	0.287	u_2	473.924	=gasu_TK("air",T_2)	T_4	793.117	=GasTK_vr("air",vr_4)			
8			P_2	1789.59	=(T_2/T_1)*rc*_P_1	u_4	588.427	=gasu_TK("air",T_4)	MEP	574.09	
9			v_2	0.10404	=R_air*T_2/P_2	v_4	0.8323	=v_1			
10											

Figure 3.13. Excel sheet developed for Example 3.3

	B	C	D	E	F	G	H	I	J	K	L	
15	Energy analysis											
16	rc	8		v_1	0.8323	=R_air*T_1/P_1		u_3	1273.784	=u_2+Q_in	q_out	381.9112
17	T_1	290 K		u_1	206.3773	=u_air(T_1,"si")		T_3	1572.595	1572.595		
18	P_1	100 kPa		vr_1	680.7629	=Vrel_air(T_1,"si")		P_3	4338.192	=(T_3/T_2)*P_2	w_net	418.0888
19	Q_in	800 kJ/kg		vr_2	85.09536	=vr_1/rc		vr_3	6.106743	=Vrel_air(T_3,"si")		
20				T_2	648.7274	=T_vrel_air(vr_2,"si")		vr_4	48.85395	=vr_3*rc	eta_1	0.522611
21	R air	0.287		u_2	473.7844	=u_air(T_2,"si")		T_4	793.1182	=T_vrel_air(vr_4,"si")	MEP	574.0909
22				P_2	1789.593	=(T_2/T_1)*rc*P_1		u_4	588.2885	=u_air(T_4,"si")		
23				v_2	0.104038	=R_air*T_2/P_2		v_4	0.8323	=v_1		
24												

Figure 3.14. Excel sheet developed for Example 3.3 using the IdealGas add-in

Table 3.2. Key parameters in the energy analysis

Parameter	Cengel and Boles [2]	Thermax	IdealGas
T_2	652.4	648.7	648.7
T_3	1575.1	1572.6	1572.6
T_4	795.6	793.1	793.1
P_2	1799.7	1789.6	1789.6
P_3	4345.0	4338.2	4338.2
q_{out}	381.83	381.91	381.91
w_{net}	418.17	418.09	418.09
η_{Otto}	0.523	0.523	0.523
MEP	574.0	574.1	574.1

Using the approximate method of analysis with fixed values of the specific heat, it can be shown that the thermal efficiency of the Otto cycle is given by [3]:

$$\eta_{otto} = 1 - (1/r_c)^{k-1} \quad (3.29)$$

Where, k is the ratio of specific heats c_p/c_v for air. Substituting $r_c = 8$ and $k = 1.4$ in Equation (3.29), the calculated thermal efficiency is 0.565. It should be noted that values of the thermal efficiency obtained by the exact and the approximate methods are both exaggerated compared to that of actual engines, but that of the variable specific heat method, which is 0.523, is less inaccurate.

3.4. Exergy analysis of the Otto cycle

Energy analyses, such as those presented in the previous sections, evaluate the general performance of energy-conversion systems using overall performance indicators such as the thermal efficiency for power-producing systems and the coefficient of performance (COP) for refrigeration systems. By comparison, *exergy* analyses which are based on the second-law of thermodynamics enable the locations, types, and true magnitudes of waste and loss to be determined. Therefore, exergy analyses can be used in design analyses of thermofluid systems to further the goal of achieving more efficient use of resources [4].

The analytical model

Exergy (ϕ) is a thermodynamic property that measures the ability of the working fluid to do useful work. Per unit mass in a closed system like that of the engine shown on Figure 3.11, exergy is given by [2]:

$$\phi = (u - u_0) - T_0(s - s_0) + P_0(v - v_0) + \frac{V^2}{2} + gz \quad (3.30)$$

Where u is the internal energy and u_0 , s_0 , and P_0 , respectively, refer to the values of the internal energy, entropy and pressure at the dead state which is the surroundings. Neglecting changes in the kinetic and potential energies, and taking into consideration that $v_3 = v_2$ in this case, the exergy input in process 2-3 is determined from:

$$\phi_{input} = (\phi_3 - \phi_2) = (u_3 - u_2) - T_0(s_3 - s_2) \quad (3.31)$$

Exergy of the working fluid can be destroyed in a process because of irreversibilities such as friction losses and heat-transfer over a finite-temperature difference. In general, the exergy destruction (x_{dest}) in a process is determined from:

$$\begin{aligned} x_{dest} &= T_0 s_{gen} = T_0 (\Delta s_{sys} - s_{in} + s_{out}) \\ &= T_0 \left((s_2 - s_1)_{sys} - \frac{q_{in}}{T_{b,in}} + \frac{q_{out}}{T_{b,out}} \right) \end{aligned} \quad (3.32)$$

Where, s_{gen} refers to the entropy generated in the process. In the Otto cycle, the processes 1-2 and 3-4 are both adiabatic and reversible. Therefore, for these two processes:

$$x_{dest} = 0 \quad (3.33)$$

However, the processes 2-3 and 4-1 both involve heat transfer with the surroundings and that makes them externally irreversible processes. While process 2-3 involves heat addition only, process 4-1 involves heat rejection only. For these two processes, exergy destructions are obtained from:

$$x_{dest} = T_0 \left((s_3 - s_2) - \frac{q_{in}}{T_H} \right) \quad \text{Process 2-3} \quad (3.34)$$

$$x_{dest} = T_0 \left((s_1 - s_4) + \frac{q_{out}}{T_L} \right) \quad \text{Process 4-1} \quad (3.35)$$

The exergy destruction of the whole Otto cycle is the sum of the exergy destructions in the heat-addition and heat-rejection processes. Since $s_2 = s_1$ and $s_4 = s_3$, the exergy destruction in the cycle becomes:

$$x_{dest} = T_0 \left(\frac{q_{out}}{T_L} - \frac{q_{in}}{T_H} \right) \quad (3.36)$$

This following example, which is based on Example 9-10 in Cengel and Boles [2], verifies the relevant Thermax functions by comparing their calculations for the exergy analysis with those given by Cengel and Boles [2].

Example 3.4. Exergy analyses of the Otto cycle

Accounting for the variation of specific heats of air with temperature, conduct an exergy analysis for the Otto cycle considered in Example 3.3 to determine:

- (i) the exergy destruction associated with the Otto cycle (all four processes as well as the cycle), assuming that heat is transferred to the working fluid from a source at 1700 K and heat is rejected to the surroundings at 290 K, and
- (ii) the exergy of the exhaust gases when they are purged.

Solution

The two Excel sheets developed for Example 3.3 were extended for this exergy analysis and Figure 3.15 shows the extension that is needed in the lower part of the sheet using Thermax functions. Table 3.3 shows the functions used in this extension. The sheet using the IdealGas add-in was extended in a similar way. The additional data needed for exergy analysis include the temperature and pressure of the surroundings, temperature of the heat source, and the sink temperature. By obtaining the required entropy values at the different states from the energy part, the two sheets determine the exergy destructions in the four processes of the cycle, the total exergy destruction, and the exergy lost in the heat-rejection process. Table 3.4 compares the calculated values to those given by Cengel and Boles [2]. The figures in the table show a good agreement between the results of the two add-ins and those given by Cengel and Boles [2].

25						
26	Exergy analysis					
27	T_0	290	Ed_12	0	Ed_cycle	245.441 kJ/kg
28	P_0	100	Ed_34	0		
29					v_0	0.8323
30	T_source	1700	Dels23	-0.75607	u_0	206.5157
31	T_sink	290	Ed_23	82.78839 kJ/kg	Dels40	0.756065
32						
33			Dels14	-0.75607	E_4	162.6526 kJ/kg
34			Ed_41	162.6526 kJ/kg		
35						

Figure 3.15. Excel sheet developed for Example 3.4 using Thermax functions

Table 3.3. Thermax functions used in exergy analysis of the Otto cycle

Cell	Cell name	Formula
F30	Dels23	=Gass0_TK("air",T_2)-Gass0_TK("air",T_3)- R_air*LN(P_2/P_3)
F31	Ed_23	=T_0*(-Dels23-Q_in/T_source)
F33	Dels14	=Dels23
F34	Ed_14	=T_0*(Dels14+q_out/T_sink)
I27	Ed_cycle	=Ed_23+Ed_41
I29	v_0	=v_1
I30	u_0	=Gasu_TK("air",T_0)
I31	Dels40	=-Dels14
I33	E_4	=(u_4-u_0)-T_0*Dels40-P_0*(v_4-v_0)

Table 3.4. Results of the Otto cycle exergy analysis

	Cengel and Boles [2]	Thermax	IdealGas
$x_{dest,2-3}$	82.2	82.8	82.79
$x_{dest,4-1}$	163.2	162.7	162.65
$x_{dest,Otto}$	245.4	245.4	245.44
ϕ_4	163.2	162.6	162.65

The figures in Table 3.4 show that two thirds of the total exergy supplied to the engine is lost during the heat-rejection process. Therefore, any design efforts that aim to minimise the loss of exergy in the heat-rejection process can effectively improve the performance of the Otto cycle. For example, the lost exergy can be used in a cogeneration system that utilises the heat for producing steam for industrial applications or for air-conditioning purposes. The figures in Table 3.4 also show that the exergy destruction in the heat-addition process are about one third of the total exergy destruction. While increasing the heat-addition temperature will improve the thermal efficiency of the cycle, it will increase the rate of exergy destruction in this process. Therefore, this temperature requires a careful consideration of the two factors among other practical considerations.

3.5. Closure

This chapter illustrates the use of Thermax property functions for the analyses of two basic gas power cycles. With respect to such cycles, property functions in the “Gas” group enable the exact variable specific-heat method to be used instead of the approximate constant-specific heat method. Both the simple and the regenerative Brayton cycles are analysed, while both energy and exergy analyses of the Otto cycle are presented. The various analyses show that the functions provided by Thermax give identical results to those given by the IdealGas add-in [1]. Thermax provides additional functions not provided by IdealGas such as the **GasTK_u** and **GasTK_h** functions that determine the temperature from a given value of internal energy or enthalpy, respectively.

References

- [1] The University of Alabama, Mechanical Engineering, Excel for Mechanical Engineering project, Internet: <http://www.me.ua.edu/excelinme/index.htm> (Last accessed July 19, 2018)
- [2] Y. A. Cengel and M. A. Boles. *Thermodynamics an Engineering Approach*, McGraw-Hill, 8th Edition, 2015
- [3] W.W. Pulkrabek, *Engineering Fundamentals of the Internal Combustion Engine*, Second Edition, Pearson Prentice Hall, 2004.
- [4] A. Bejan, G. Tsatsaronis, M. Moran, *Thermal Design & Optimization*, John Wiley & Sons, 1996.
- [5] M.J. Moran and H.N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 5th edition, John Wiley, & Sons. Inc. 2006

Exercises

1. Figure 3.10 shows that the net output work and thermal efficiency of the regenerative Brayton cycle reach their maximum values at different pressure ratios; which is about 8 for the maximum net work output and about 5 or less for the maximum thermal efficiency. Use Solver to determine the exact values of the two optimum pressure ratios.
2. A regenerative gas turbine with intercooling and reheat operates at steady state. Air enters the compressor at 100 kPa, 300 K with a mass flow rate of 5.8 kg/s. The pressure ratio across the two-stage compressor is 10. The pressure ratio across the two-stage turbine is also 10. The intercooler and reheater each operate at 300 kPa. At the inlets to the turbine stages, the temperature is 1400 K. The temperature at the inlet to the second compressor stage is 300 K. The isentropic efficiency of each compressor and turbine stage is 80%. The regenerator effectiveness is 80%. Figure 3.P2 shows the T - s diagram of the regenerative gas turbine cycle.

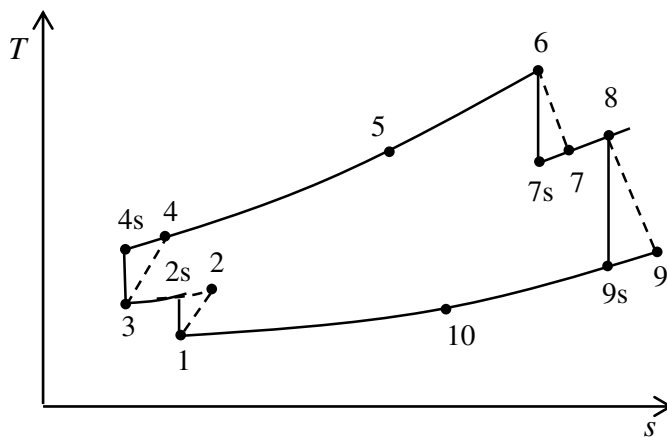


Figure 3.P2. T - s diagram for the regenerative gas turbine with intercooling

Develop an Excel sheet to determine: **(a)** the thermal efficiency, **(b)** the back work ratio, **(c)** the net power developed, in kW. Compare your solution with that of Example 9.11 in Moran and Shapiro [5].

- The air-standard Diesel cycle shown on Figure 3.P3 operates with a compression ratio of 18. At the beginning of the compression process the temperature is 300 K and the pressure is 0.1 MPa. The cutoff ratio for the cycle is 2. Using Thermax or any other property add-in, develop an Excel sheet to determine (a) the temperature and pressure at the end of each process of the cycle, (b) the thermal efficiency, (c) the mean effective pressure, in MPa. Compare your solution with that of Example 9.2 in Moran and Shapiro [5].

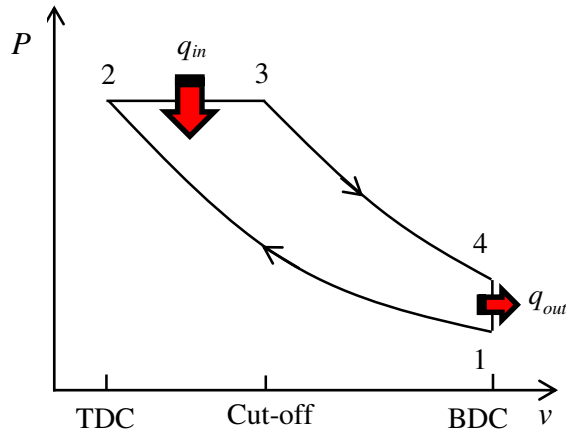


Figure 3.P3. P - v diagram of the Diesel cycle