



GINA CODY
SCHOOL OF ENGINEERING
AND COMPUTER SCIENCE

Department of Mechanical,
Industrial and Aerospace Engineering

MECH 351

LABORATORY MANUAL (WINTER 2024)

THERMODYNAMICS II
H 1063

EMERGENCY • URGENCE

CAMPUS SAFETY AND PREVENTION SERVICES
514-848-3717
SERVICE DE LA PROTECTION ET PRÉVENTION

BUILDING EVACUATION

When you hear the fire alarm, YOU MUST LEAVE THE BUILDING IMMEDIATELY.

STOP your work.

GATHER all your personal belongings.

LEAVE calmly, by closing doors and windows behind you, and go to the nearest emergency exit door or stairwell.

MOVE AWAY from the building, once outside.

Help people with reduced mobility

If you encounter a person with reduced mobility that cannot use the emergency stairwells during an evacuation, the following procedure must be used:

1. Escort the person to the nearest emergency stairwell, remaining outside the stairwell.
2. Use a telephone (fire department, emergency or cellular) to contact Campus Safety and Prevention Services and advise them that you are with a mobility reduced person; if not available, send someone to advise Security.
3. Campus Safety personnel or Emergency Responders (CERT members) will come to assist you.
4. In the presence of danger, such as smoke, alert Campus Safety and move the person inside the stairwell ensuring the door is closed behind you.

ÉVACUATION DES LIEUX

Dès que vous entendez l'alarme incendie, QUITTEZ LE BÂTIMENT IMMÉDIATEMENT.

CESSEZ toute activité.

RASSEMBLEZ vos effets personnels.

QUITTEZ la salle dans le calme, en fermant les portes et fenêtres derrière vous, et dirigez-vous vers l'escalier ou l'issue de secours la plus proche.

ÉLOIGNEZ-VOUS du bâtiment une fois à l'extérieur.

Aide aux personnes à mobilité réduite

1. Accompagnez-la jusqu'à l'escalier de secours le plus proche en demeurant à l'extérieur de la cage d'escalier.
2. Utilisez un téléphone (service des incendies, urgence ou cellulaire) ou dépêchez quelqu'un pour aviser la Sécurité que vous êtes avec une personne à mobilité réduite.
3. Attendez que le personnel du Service de la protection ou les intervenants d'urgence viennent vous aider.
4. S'il y a présence d'un danger (de la fumée, par exemple), le Service de la protection et emmenez la personne à l'intérieur de la cage d'escalier en vous assurant de refermer la porte derrière vous.

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CONTACTS

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Name: _____

E-Mail: _____

LABORATORY PARTNERS *(Fill in by student)*

Name: _____

E-Mail: _____

Phone: _____

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E-Mail: _____

Phone: _____

Name: _____

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Phone: _____

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LABORATORY CALENDAR

Laboratory Calendar is subject to change after time of printing this manual. The most up to date calendar can be found posted outside the laboratory.

	MOH	TUES	WED	THURS	FRI	
JANUARY	8	9	10	11	12	LAB 1
	Lab EI-X: 08:45-10:35 Lab OI-X: 10:45-12:35 Lab HI-X: 12:45-14:35 Lab QI-X: 15:45-17:35	Lab CI-X: 08:45-10:35 Lab LI-X: 10:45-12:35 Lab XI-X: 14:45-16:35	Lab SI-X: 12:45-14:35 Lab VI-X: 14:45-16:35	Lab MI-X: 10:45-12:35 Lab CC-X: 14:45-16:35	Lab AI-X: 08:45-10:35	
	22	23	24	25	26	
	Lab GI-X: 10:45-12:35 Lab JI-X: 12:45-14:35 Lab PI-X: 15:45-17:35	Lab FF-X: 10:45-12:35 Lab YI-X: 14:45-16:35	Lab RI-X: 12:45-14:35 Lab UI-X: 14:45-16:35	Lab BB-X: 08:45-10:35 Lab NI-X: 10:45-12:35 Lab AA-X: 14:45-16:35	Lab NI-X: 08:45-10:35 Lab TI-X: 11:45-13:35 Lab BI-X: 14:45-16:35	
	29	30	31	1	2	
	Lab EI-X: 08:45-10:35 Lab OI-X: 10:45-12:35 Lab HI-X: 12:45-14:35 Lab QI-X: 15:45-17:35	Lab CI-X: 08:45-10:35 Lab LI-X: 10:45-12:35 Lab XI-X: 14:45-16:35	Lab SI-X: 12:45-14:35 Lab VI-X: 14:45-16:35	Lab MI-X: 10:45-12:35 Lab CC-X: 14:45-16:35	Lab AI-X: 08:45-10:35	
FEBRUARY	5	6	7	8	9	LAB 2 (H 841)
	Lab GI-X: 10:45-12:35 Lab JI-X: 12:45-14:35 Lab PI-X: 15:45-17:35	Lab FF-X: 10:45-12:35 Lab YI-X: 14:45-16:35	Lab RI-X: 12:45-14:35 Lab UI-X: 14:45-16:35	Lab BB-X: 08:45-10:35 Lab NI-X: 10:45-12:35 Lab AA-X: 14:45-16:35	Lab NI-X: 08:45-10:35 Lab TI-X: 11:45-13:35 Lab BI-X: 14:45-16:35	
	12	13	14	15	16	
	Lab EI-X: 08:45-10:35 Lab OI-X: 10:45-12:35 Lab HI-X: 12:45-14:35 Lab QI-X: 15:45-17:35	Lab CI-X: 08:45-10:35 Lab LI-X: 10:45-12:35 Lab XI-X: 14:45-16:35	Lab SI-X: 12:45-14:35 Lab VI-X: 14:45-16:35	Lab MI-X: 10:45-12:35 Lab CC-X: 14:45-16:35	Lab AI-X: 08:45-10:35	
	19	20	21	22	23	
	Lab GI-X: 10:45-12:35 Lab JI-X: 12:45-14:35 Lab PI-X: 15:45-17:35	Lab FF-X: 10:45-12:35 Lab YI-X: 14:45-16:35	Lab RI-X: 12:45-14:35 Lab UI-X: 14:45-16:35	Lab BB-X: 08:45-10:35 Lab NI-X: 10:45-12:35 Lab AA-X: 14:45-16:35	Lab NI-X: 08:45-10:35 Lab TI-X: 11:45-13:35 Lab BI-X: 14:45-16:35	
26	27	28	29	1	LAB 3 LAB 4 BREAK PROJECT (ALL SECTIONS)	
MARCH	4	5	6	7		8
	Lab EI-X: 08:45-10:35 Lab OI-X: 10:45-12:35 Lab HI-X: 12:45-14:35 Lab QI-X: 15:45-17:35	Lab CI-X: 08:45-10:35 Lab LI-X: 10:45-12:35 Lab XI-X: 14:45-16:35	Lab SI-X: 12:45-14:35 Lab VI-X: 14:45-16:35	Lab MI-X: 10:45-12:35 Lab CC-X: 14:45-16:35		Lab AI-X: 08:45-10:35
	11	12	13	14		15
	Lab GI-X: 10:45-12:35 Lab JI-X: 12:45-14:35 Lab PI-X: 15:45-17:35	Lab FF-X: 10:45-12:35 Lab YI-X: 14:45-16:35	Lab RI-X: 12:45-14:35 Lab UI-X: 14:45-16:35	Lab BB-X: 08:45-10:35 Lab NI-X: 10:45-12:35 Lab AA-X: 14:45-16:35		Lab NI-X: 08:45-10:35 Lab TI-X: 11:45-13:35 Lab BI-X: 14:45-16:35
	18	19	20	21		22
	Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	
25	26	27	28	29		
Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	Good Friday		
APRIL	1	2	3	4	5	
	Easter Monday	Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	
	8	9	10	11	12	
Open: 08:00-15:45	Open: 08:00-15:45	Open: 08:00-15:45	08:45-16:00 EVALUATION (DAY 1)	08:45-16:00 EVALUATION (DAY 2)		

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GENERAL LABORATORY SAFETY RULES

FOLLOW RELEVANT INSTRUCTIONS

- Before attempting to install, commission or operate equipment, all relevant suppliers' / manufacturers' instructions and local regulations should be understood and implemented.
- It is irresponsible and dangerous to misuse equipment or ignore instructions, regulations or warnings.
- Do not exceed specified maximum operating conditions (e.g. temperature, pressure, speed etc.).

INSTALLATION/COMMISSIONING

- Use lifting table where possible to install heavy equipment. Where manual lifting is necessary beware of strained backs and crushed toes. Get help from an assistant if necessary. Wear safety shoes where appropriate.
- Extreme care should be exercised to avoid damage to the equipment during handling and unpacking. When using slings to lift equipment, ensure that the slings are attached to structural framework and do not foul adjacent pipe work, glassware etc.
- Locate heavy equipment at low level.
- Equipment involving inflammable or corrosive liquids should be sited in a containment area or bund with a capacity 50% greater than the maximum equipment contents.
- Ensure that all services are compatible with equipment and that independent isolators are always provided and labelled. Use reliable connections in all instances, do not improvise.
- Ensure that all equipment is reliably grounded and connected to an electrical supply at the correct voltage.
- Potential hazards should always be the first consideration when deciding on a suitable location for equipment. Leave sufficient space between equipment and between walls and equipment.
- Ensure that equipment is commissioned and checked by a competent member of staff permitting students to operate it.

OPERATION

- Ensure the students are fully aware of the potential hazards when operating equipment.
- Students should be supervised by a competent member of staff at all times when in the laboratory. No one should operate equipment alone. Do not leave equipment running unattended.
- Do not allow students to derive their own experimental procedures unless they are competent to do so.

MAINTENANCE

- Badly maintained equipment is a potential hazard. Ensure that a competent member of staff is responsible for organizing maintenance and repairs on a planned basis.
- Do not permit faulty equipment to be operated. Ensure that repairs are carried out competently and checked before students are permitted to operate the equipment.

ELECTRICITY

- Electricity is the most common cause of accidents in the laboratory. Ensure that all members of staff and students respect it.
- Ensure that the electrical supply has been disconnected from the equipment before attempting repairs or adjustments.
- Water and electricity are not compatible and can cause serious injury if they come into contact. Never operate portable electric appliances adjacent to equipment involving water unless some form of constraint or barrier is incorporated to prevent accidental contact.
- Always disconnect equipment from the electrical supply when not in use.

AVOIDING FIRES OR EXPLOSION

- Ensure that the laboratory is provided with adequate fire extinguishers appropriate to the potential hazards.
- Smoking must be forbidden. Notices should be displayed to enforce this.
- Beware since fine powders or dust can spontaneously ignite under certain conditions. Empty vessels having contained inflammable liquid can contain vapor and explode if ignited.
- Bulk quantities of inflammable liquids should be stored outside the laboratory in accordance with local regulations.
- Storage tanks on equipment should not be overfilled. All spillages should be immediately cleaned up, carefully disposing of any contaminated cloths etc. Beware of slippery floors.
- When liquids giving off inflammable vapors are handled in the laboratory, the area should be properly ventilated.
- Students should not be allowed to prepare mixtures for analysis or other purposes without competent supervision.

HANDLING POISONS, CORROSIVE OR TOXIC MATERIALS

- Certain liquids essential to the operation of equipment, for example, mercury, are poisonous or can give off poisonous vapors. Wear appropriate protective clothing when handling such substances.
- Do not allow food or drink to be brought into or consumed in the laboratory. Never use chemical beakers as drinking vessels
- Smoking must be forbidden. Notices should be displayed to enforce this.
- Poisons and very toxic materials must be kept in a locked cupboard or store and checked regularly. Use of such substances should be supervised.

AVOID CUTS AND BURNS

- Take care when handling sharp edged components. Do not exert undue force on glass or fragile items.
- Hot surfaces cannot, in most cases, be totally shielded and can produce severe burns even when

not visibly hot. Use common sense and think which parts of the equipment are likely to be hot.

EYE/EAR PROTECTION

- Goggles must be worn whenever there is risk to the eyes. Risk may arise from powders, liquid splashes, vapors or splinters. Beware of debris from fast moving air streams.
- Never look directly at a strong source of light such as a laser or Xenon arc lamp. Ensure the equipment using such a source is positioned so that passers-by cannot accidentally view the source or reflected ray.
- Facilities for eye irrigation should always be available.
- Ear protectors must be worn when operating noisy equipment.

CLOTHING

- Suitable clothing should be worn in the laboratory. Loose garments can cause serious injury if caught in rotating machinery. Ties, rings on fingers etc. should be removed in these situations.
- Additional protective clothing should be available for all members of staff and students as appropriate.

GUARDS AND SAFETY DEVICES

- Guards and safety devices are installed on equipment to protect the operator. The equipment must not be operated with such devices removed.
- Safety valves, cut-outs or other safety devices will have been set to protect the equipment. Interference with these devices may create a potential hazard.
- It is not possible to guard the operator against all contingencies. Use commonsense at all times when in the laboratory.
- Before starting a rotating machine, make sure staff are aware how to stop it in an emergency.
- Ensure that speed control devices are always set to zero before starting equipment.

FIRST AID

- If an accident does occur in the laboratory it is essential that first aid equipment is available and that the supervisor knows how to use it.
- A notice giving details of a proficient first-aider should be prominently displayed.
- A short list of the antidotes for the chemicals used in the particular laboratory should be prominently displayed.

LABORATORY PROTOCOL

GENERAL

Each lab presented in this manual is performed on a bi-weekly basis. The order of performance of each lab is followed unless specified otherwise by the Laboratory Specialist.

Students are divided into groups of three or four to perform the experiment. All students are required to work together within the group throughout the semester. No switching groups in mid-stream or splitting groups is allowed. Internal conflicts within the group are handled by the professor. The same group formation in the laboratory is employed for the project. Consult the project Moodle site for more information.

The student must come to the laboratory at their registered section. Otherwise, the student is not allowed to attend unless they have prior permission from the Laboratory Specialist.

Bring a USB flash drive to copy data files when required.

In order that the laboratory session is conducted in the most meaningful manner possible, it is imperative that each student read, study, and understand the lab to be conducted prior to coming to the laboratory. The student should also read and understand the laboratory safety guidelines. Failure to follow these guidelines will result in expulsion from the laboratory.

An attendance sheet is circulated and it is the responsibility of the student to sign it at each lab session. The lab instructor is not expected to remember if the student attended and later forgot to sign the attendance sheet.

The student is required to complete all given laboratory tasks within the allotted laboratory time (110 minutes). There is no extension outside the scheduled time. Walking out of the laboratory during the lab time period (i.e. to go print the lab report, park the car etc.) except to go to the bathroom results in a 20 mark deduction for the experiment.

At the end of each lab, the laboratory instructor must sign the completed data sheet provided in this manual. This signed sheet must be incorporated at the end of the laboratory report to be submitted by the group to receive credit. For saved data on a USB flash drive, print the file and attach to the lab report without a signature.

No food or drink allowed in the laboratory. Cellular phones must be muted and not visible during the laboratory.

COMING LATE

Arriving to the laboratory between 10 to 29 minutes late from the scheduled start for whatever reason (i.e. metro breakdown, car accident, traffic, bad weather etc.) is deducted 20 marks for the experiment.

Arriving 30 minutes after the start of the scheduled lab results in a no credit for the experiment and not allowed to enter the laboratory..

There are no makeup labs for coming late to the laboratory.

MISSING A LAB

All issues missing a lab are handled by the Laboratory Specialist.

There are no makeup labs except for statutory holidays.

The only accepted reasons for missing a lab are:

- Medical (Self only)
- Government Related
- Concordia Event

The student must provide third-party proof (name and date must be indicated) within 24 hours from the scheduled experiment to the Laboratory Specialist. Students have a maximum of TWO such instances for the semester. Filling out the Concordia Short Term Absence form covering the missed lab counts as an instance.

Once accepted, arrangements are made to make up the lab with another lab section. The student must contribute in writing the lab report with their original lab group. If it is not possible to make up the lab due to schedule conflicts, the student must contact the professor to discuss on how the missed lab is to be handled in terms of the grade.

LATE REGISTRATION

Registering late for the course (i.e. after the labs have started at the beginning of the semester) must attend their registered section without exception. If a student officially registers for a lab section which has completed the first lab, the student must notify the Laboratory Specialist either by e-mail or in person. The Laboratory Specialist will make arrangements for the student to possibly attend another lab section for this one time only. If it is not possible to make up the lab due to schedule conflicts, the student must contact the professor to discuss on how the missed lab is to be handled in terms of the grade. The student returns to their registered lab section for the next lab.

DROPPING COURSE DURING THE SEMESTER

Out of courtesy, the student should advise their laboratory partners and the Laboratory Specialist in the event of this occurrence. The student's previous performed labs are deleted from the record.

If a group reduces to one member then the student is moved to another group. Two members in a group is still valid.

LABORATORY REPORTS

GENERAL

Each group submits a complete written hardcopy report covering each lab performed. The report is to be the group's own work. The report is written in the third person, past tense (for procedures executed, data taken, and results obtained) and should be self-sufficient. In other words, the reader should not need to consult the references in order to understand the report. Correct English and spelling should be used. The reports are practice for writing technical reports similar to those, which are required by engineers engaged in industry and engineering practice.

The reports must be typed using a word processor and stapled or bounded only (i.e. no paper clips). All pages, equations, figures, graphs and tables must be numbered. Figures, tables, graphs, etc., must have titles and be introduced in a sentence in the text of the report. Figures must have axis labels that name the variable as well as giving its symbol and units if appropriate.

Figures, graphs, and tables must be neat and clear. Figures and graphs should be generated on the computer through drawing and plotting software. Choose scales that are appropriate to the range of data and that can be easily read. Leave room on the paper for scales, labels, and titles.

SPECIFICATIONS

In order to observe the accepted rules of good writing form, the following specifications for the general makeup of the report are suggested:

- Use 8 ½ x 11 inch white paper.
- Write the report with a word processor.
- USE ONE SIDE OF THE PAPER ONLY.
- A SINGLE GRAPH SHOULD BE REPRESENTED USING THE ENTIRE SHEET OF PAPER. MULTIPLE GRAPHS ON ONE SHEET ARE NOT ACCEPTABLE.
- Graphs axes should be clearly labeled, including units where appropriate.
- Discrete experimental data that are plotted on appropriate graphs should be designated with small symbols, such as circles, to distinguish these data from those represented by curves fitted through them either intuitively or statistically or by mathematical model. If more than one dependent variable (ordinate) is presented on a graph, each variable should have a different symbol.
- When mathematically fitting curves to experimental data, use appropriate judgment. Just because a 6th order polynomial can fit exactly to 7 points does not mean that it is the appropriate curve for this experimental data (i.e. the distribution may actually be linear or quadratic). Instead look at the trend of the data and avoid the pitfall of many students in letting the computer chose the best curve fit. As a general rule, the lower the complexity of the curve fit that represents the data trends, the better.

FORMAT

The following report outline is required for content and order of presentation:

- **TITLE PAGE:** Must include lab title, date performed, student names in the group with corresponding identification numbers, **lab section and assigned group letter (A or B)**. Another group number is assigned for the project. Consult the project Moodle site for more information..
- **OBJECTIVE:** State the objective(s) clearly in a concise manner in your own words.
- **INTRODUCTION:** Background information preparing the reader as to what is done during the lab. Do not copy what is written in the manual. Any theory mentioned or relevant information must be referenced.
- **PROCEDURE:** A general description of the procedure should be given. This description should be comprehensive, but brief. It should include a generic list of equipment used and a sketch to show how the equipment items are related. The enumeration and detailed description of multitudinous mechanical operations or sequence of such operations such as closing switches, reading instruments, turning knobs and so forth, should in general be avoided. However, when a specific method of mechanical operation or sequence of such operations is necessary in order to insure the validity or accuracy of the test data, it is important that the essential details be included in the description. Note that it is unacceptable to simply use or copy the procedural instructions from the manual.
- **RESULTS:** Answer all the questions posed in the laboratory manual. All observed and calculated data should be tabulated when possible. Use significant figures for all your measurements and calculations. Headings and subheadings (titles) identifying items of data or sets of data should be used.
 - **SAMPLE CALCULATIONS:** Show a sample of a complete calculation of each type involved in the determination of calculated data and the solution of problems. These sample calculations should be first shown in symbolic form with all symbols properly defined. Then numerical data should be used with units shown in the actual calculations.
 - **GRAPHS:** See Specifications section.
- **DISCUSSION:** MOST IMPORTANT SECTION OF THE ENTIRE REPORT. IT SHOULD BE A COMPLETE DISCUSSION OF THE RESULTS OBTAINED. Part of this discussion should deal with the accuracy or reliability of the results. It is suggested that this section consist, when applicable, of a careful treatment of the effect upon the results of the following:
 - Comparison of the results obtained with those that would reasonably have been expected from a consideration of the theory involved in the problem. Whenever the theory is apparently contradicted, the probable reasons should be discussed.
 - Errors resulting from the necessity of neglecting certain factors because of physical limitations in the performance of the test.
 - When results are given in graphical form as curves, the shape of each curve should be carefully explained. Such an explanation should state the causes or the particular shape the curve may have. It is not sufficient simply to state that a particular curve has positive slope, the reason for such a slope should be given. If the slope is not constant, that is, if the curve is not a straight line, its nonlinearity should also be explained.
 - Any original conclusions drawn as a consequence of the laboratory procedure and a study of the results obtained should be given in this section and should be justified by the discussion.
 - Constructive criticism of any phase of the experiment that may seem pertinent may also be included here.
- **CONCLUSIONS:** In this section the conclusions which were supported and drawn in the Discussion are succinctly restated, usually as a numbered list. No new information should appear in this section. All justification of conclusions should have occurred in prior sections.

- **SOURCES OF MEASUREMENT ERRORS:** An error is a measure of the range of values within which the desired value x lies with a certain probability. For example, if x lies between $x_1 + \Delta x$ and $x_1 - \Delta x$ then $x = x_1$ with an error of Δx , usually written as $x = x_1 \pm \Delta x$. Please note that Δx is considered a positive value. Δx is the absolute error and has the same units as x . At times, the error is expressed as a ratio between the absolute error and the actual value, $\Delta x/x$. This is the relative error in x . The relative error is always a positive value (we calculate in effect $|\Delta x/x|$). It is dimensionless and often expressed as a percentage.

Consider one wants to find the value of x by measuring values a, b, c, \dots . This relationship can be described by $x = f(a, b, c, \dots)$, or x is some function of a, b, c, \dots . Since a, b, c, \dots are measured values, with errors $\Delta a, \Delta b, \Delta c, \dots$ respectively, x will also have an error, namely Δx . If a, b, c, \dots are independent we can write:

$$\Delta x = \frac{\partial f}{\partial a} \Delta a + \frac{\partial f}{\partial b} \Delta b + \frac{\partial f}{\partial c} \Delta c + \dots \quad (1)$$

where $\frac{\partial f}{\partial a}$ is the partial derivative of f with respect to a .

The maximum possible error in Δx is obtained when all terms in (1) are positive, or

$$\Delta x = |\frac{\partial f}{\partial a} \Delta a| + |\frac{\partial f}{\partial b} \Delta b| + |\frac{\partial f}{\partial c} \Delta c| + \dots \quad (2)$$

Or, given that $\Delta a, \Delta b, \Delta c, \dots$ are positive,

$$\Delta x = \frac{\partial f}{\partial a} \Delta a + \frac{\partial f}{\partial b} \Delta b + \frac{\partial f}{\partial c} \Delta c + \dots \quad (3)$$

Addition or Subtraction:

If $x = f(a, b) = a + b$

then $x + \Delta x = (a + \Delta a) + (b + \Delta b) = (a + b) + (\Delta a + \Delta b)$

or $\Delta x = \Delta a + \Delta b$

(4)

Multiplication:

If $x = f(a, b) = a b$

then $x + \Delta x = (a + \Delta a) (b + \Delta b) = (a b) + (b \Delta a + a \Delta b) + \text{higher order terms}$

or $\Delta x = |b| \Delta a + |a| \Delta b = |ab| \frac{\Delta a}{|a|} + |ab| \frac{\Delta b}{|b|} = |ab| (\frac{\Delta a}{|a|} + \frac{\Delta b}{|b|})$

or $\Delta x/x = \Delta a/|a| + \Delta b/|b|$

(5)

Division:

If $x = f(a, b) = a / b$

then $x + \Delta x = (a + \Delta a) / (b + \Delta b) = (a + \Delta a) (b - \Delta b) / \{(b - \Delta b) (b + \Delta b)\} = \{(a b) + (b \Delta a - a \Delta b) + \text{higher order terms}\} / (b^2 + \text{higher order terms}) = a / b + (b \Delta a - a \Delta b) / b^2$

or $\Delta x = (|b| \Delta a + |a| \Delta b) / b^2$

or $\Delta x/x = (|b| \Delta a + |a| \Delta b) / |ab|$

(6)

Power or Roots:

If $x = f(a) = a^p$ (note that p does not have to be an integer)

then $x + \Delta x = (a + \Delta a)^p = a^p + p a^{p-1} \Delta a + \text{higher order terms}$

or $\Delta x = |p a^{p-1}| \Delta a = |p a^p \Delta a / a|$

or $\Delta x/x = |p \Delta a / a|$

(7)

Given a and b are measured values where $a = 30.6 \pm 0.2$ and $b = 18.6 \pm 0.1$. Calculate x, where:

1. **$x = a + b$.** $x = (30.6 \pm 0.2) + (18.6 \pm 0.1) = 49.2 \pm 0.3$. The relative error is $0.3/49.1 = 0.00611$, which we should write as 0.006 or 0.6%.
 2. **$x = a - b$.** $x = (30.6 \pm 0.2) - (18.6 \pm 0.1) = 12 \pm 0.3$. We have to rewrite this as $x = 12.0 \pm 0.3$. The relative error is $0.3/12.0 = 0.025$ or 2.5%, which we could leave as is or write as 0.03 or 3%.
 3. **$x = a b$.** $x = (30.6 \pm 0.2) * (18.6 \pm 0.1) = 30.6 * 18.6 \pm (0.1 * 30.6 + 0.2 * 18.6) = 569.16 \pm 6.78$. We have to rewrite this as $x = 569 \pm 7$. The relative error is $7/569 = 0.0123$, which we should write as 0.012 or 1.2%. Another way to calculate the absolute error is to first calculate the relative error, using equation (5). Thus, the relative error is $0.2/30.6 + 0.1/18.6 = 0.0065 + 0.0054 = 0.0119$, which we should write as 0.012 or 1.2%. The absolute error is $0.012 * 569 = 6.828$, which we should write as 7.
 4. **$x = a^{2.2}$.** $x = 30.6^{2.2} = 1856.04$. Since our original measurement a has three significant digits, we probably cannot have more than that in our calculation for x. Using equation (7) we find that the relative error is $2.2 (0.2/30.6) = 2.2 * 0.0065 = 0.014$ or 1.4%. That means an absolute error of $0.014 * 1856 = 25.98$. Although we may want to write $x = 1856 \pm 26$, the correct answer is $186 * 10^1 \pm 3 * 10^1$.
- **REFERENCES:** Whenever referring to published sources of this kind, for example when quoting technical specifications or specialist theory, full particulars of the source in a numbered list of references must be included. Below are several examples that show the correct format for journals, books and web sites.
 - Journal: [1] Hamilton, R. J., & Bowers, B. , The Kinetic Theory of Molecular Gases: A Roy Model Exemplar. *Physical Science Quarterly*, 20, 2007, pp 254-264.
 - Book: [2] Hyde, J. S. & Delamater, J., *Introduction to Physics*, (10th edition) New York: McGraw-Hill, 2008, pp 220-227.
 - Website: [3] cms.mit.edu/research/index.php (Accessed October 2009)

Note: Every item in the reference list must be referred to by inserting its number in the appropriate section of text. This is done using square brackets.

- **APPENDICES:** Materials that support the report but are not essential to the reader's understanding of it are included here. The data sheet and printed data from a digital file should included here.

ORIGINALITY FORM

This form must be completed by each student and submitted to the lab instructor during the first experiment. A late penalty (i.e. overall lab grade deduction) is assessed each day the form is not submitted after the second experiment. Failure to submit this form results in no credit for the lab. A copy of the form can be found at the end of this manual. For more information, go to encs.concordia.ca/current-students/forms-and-procedures/expectation-of-originality.

PLAGIARISM

The student is responsible for their own work and is expected to write their own thoughts. Plagiarism is a serious problem. If caught plagiarizing, the student forfeits the right to attend the laboratory, receive a failing lab grade and be removed from the university by due process as stated in the student handbook.

Plagiarism is any portrayal of information as your own when not truly yours. Plagiarism is rewriting another student's report. Plagiarism is turning in the same report from a previous year even if a few words are moved around. Plagiarism is forgetting to cite information that was obtained outside your brain. Plagiarism is cheating.

Avoid plagiarism by signing the "Originality Form" and submitting it to the lab instructor as a separate attachment with the *first* lab report *one time only*. The signed form claims this is the product of your own work, that the material presented has been created by the student and properly cited and that no other person created or prepared the lab report.

SUBMISSION

Each group must submit their report to the laboratory instructor at the following lab (i.e. exactly 2 weeks from the performance date of the lab; study break does NOT count as a week). If a lab report deadline falls on a statutory holiday, the report is to be submitted to the Laboratory Specialist the following business day at specified time deadline to be announced. The final lab report is to be submitted to the Laboratory Specialist two weeks from the date of performance.

Electronic submissions by e-mail (i.e soft copies) are considered invalid. The lab instructor or Laboratory Specialist immediately disregards these type of submissions and have no weight. Hard copies of lab reports are the form accepted.

Submission of a late lab report is subject to a 25 mark deduction. Late lab reports are to be submitted to the Laboratory Specialist only within 0 to 24 hours from the actual deadline, otherwise, no credit is given.

The corrected report is returned to the group in the next experiment for viewing only. The lab instructor keeps the lab report. Failure to return any lab report to the lab instructor results in an INCOMPLETE GRADE (i.e. no grade is recorded for the entire group).

GRADING

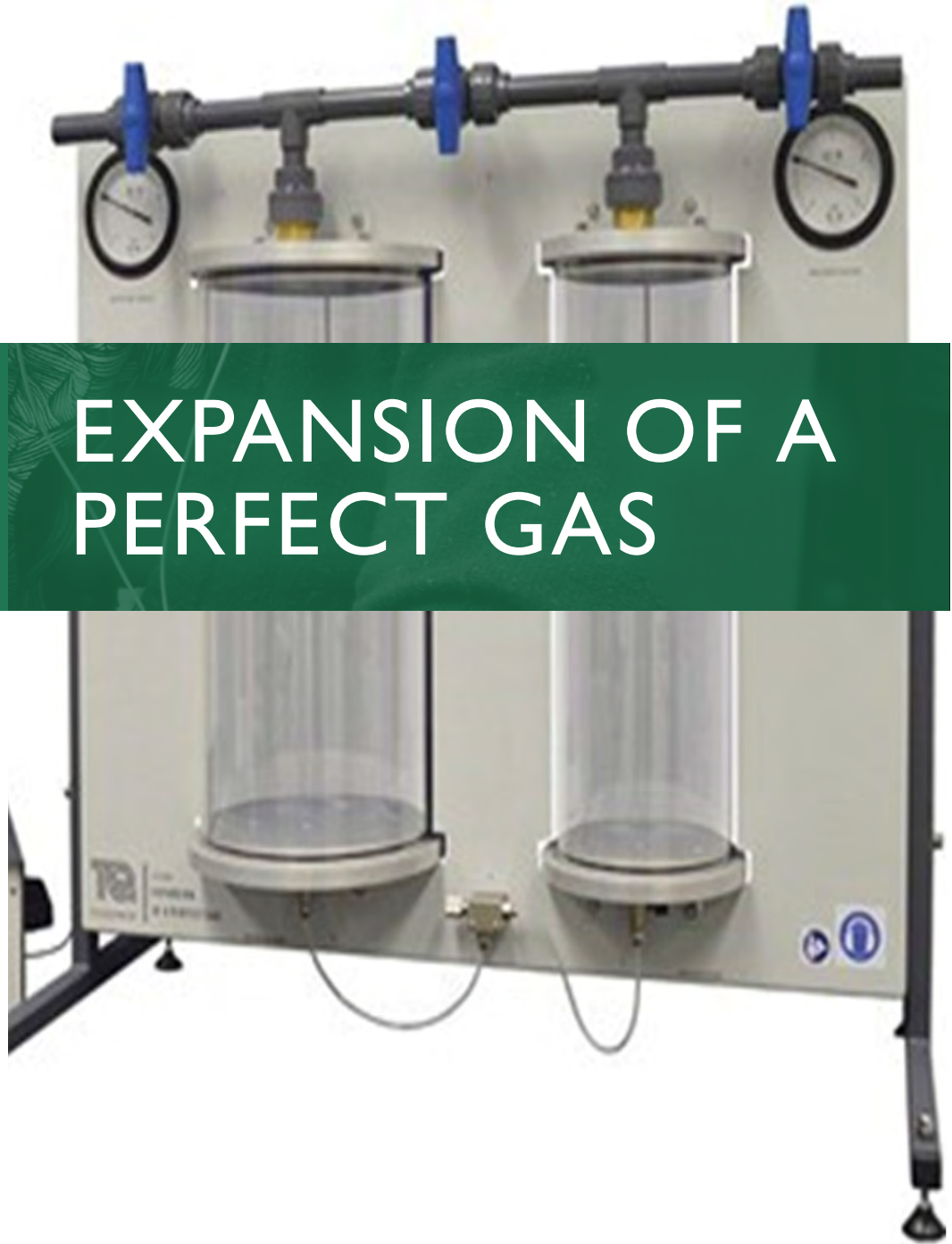
The grading breakdown for each lab report out of 100 marks is as follows:

- Presentation (20%)
- Results (40%)
- Discussion/Conclusion (40%)

LAB

1

EXPANSION OF A PERFECT GAS



INTRODUCTION

A perfect gas is a theoretical gas, it differs from real gasses in a way that makes calculations easier to handle. It is therefore suitable to use for experiments to understand the thermodynamics of fluid and the basic laws of thermodynamics. Particularly the relationships between pressure (P), temperature (T) and volume (V), for example Boyle's law, Gay-Lussac's law, and the ideal gas equation of state. Although a perfect gas does not exist, it is a helpful model that provides a valuable approximation reference for real gases to compare and evaluate how the behavior of real gases deviate from those of ideal gasses.

The expansion of a gas is a simple process without much chemical change, especially for the air that behaves as an ideal gas. This expansion process is commonly encountered in many practical applications (i.e.: combustion engines, air-cycle refrigeration machines, fire extinguishers, hot air balloons) etc.

TecQuipment's Expansion of a Perfect Gas (TD1004V) is a simple-to-use, fundamental experiment apparatus that demonstrates the behavior of an ideal gas and its basic thermodynamic processes. It can be used to demonstrate air compression and expansion such as isothermal, isochoric, adiabatic, polytropic and constant internal energy processes. The apparatus can be used to explore thermodynamic knowledge relating to the First and Second Laws of Thermodynamics including the non- flow energy system equation, reversible and irreversible processes and entropy.

DESCRIPTION

The Expansion of a Perfect Gas TD1004V is a self-contained bench-top experiment apparatus that is convenient to use in a laboratory. Figure 1.1 shows the main parts of the apparatus, it includes two T-legs with adjustable feet, holding a steel panel mounted in which are two different-sized clear vessels. Each vessel houses a fast response thermocouple and pressure sensor. Each vessel is also connected to a mechanical pressure gauge to show the state of the vessel when not connected to the control box.

The vessels are connected via a large bore pipe. Ball valves (V_1 , V_2 and V_3) on this pipe allow the vessels to be isolated from each other and the surrounding atmosphere as required for experiments. The vessels are also connected via a small-bore pipe with a needle valve (V_5) to accurately control the flow between the vessels. A further two ball valves (V_4 and V_6) allow the vessels to isolate the small-bore pipe for some experiments.

The man panel also features a third thermocouple (T_3) to measure the ambient temperature. This is key for the experiments to ensure that the temperature inside the vessels matches the ambient temperature during certain points during the experiments.

Details of TD1004V's main components are shown in the following sections.

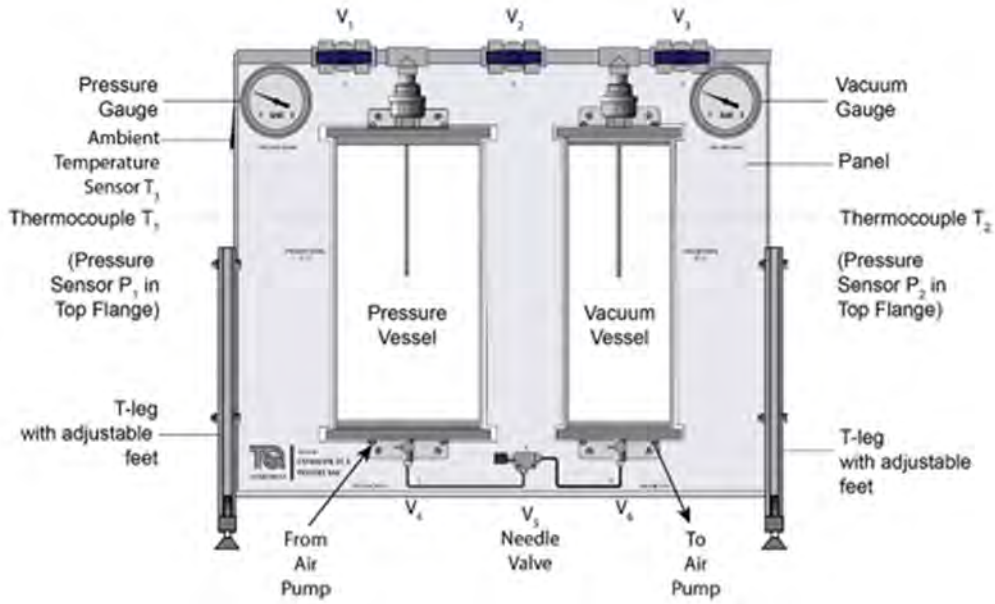


Figure 1.1: Front View of Expansion of a Perfect Gas Apparatus Main Components

KEY COMPONENTS

VACUUM VESSEL

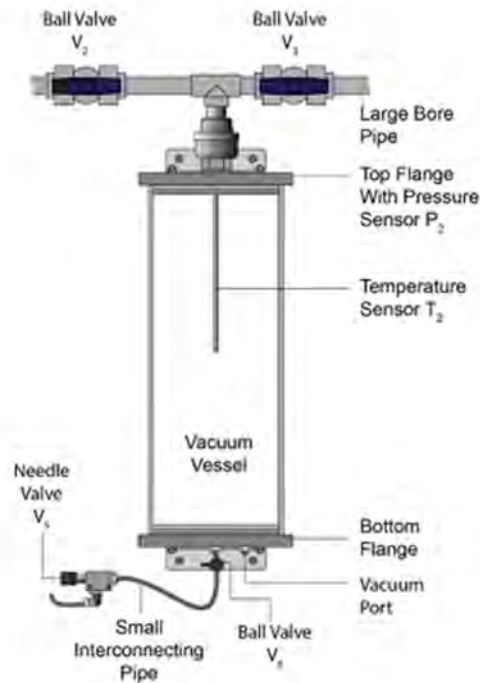


Figure 1.2: Vacuum Vessel

This is a clear acrylic cylinder mounted to the right of the Panel. This vessel is used as either a vacuum or atmospheric tank for the experiments in TD1004V (see Figure 1.2) The vacuum vessel volume is 0.0102 m^3 .

The top flange is fitted with the vacuum pressure and temperature sensors (P2 and T2). It is also connected to the pressure vessel and atmosphere by the large bore pipe.

The base flange features a vacuum port that can be connected to the vacuum port on the control box. This is self-sealing so it will automatically seal when the connecting pipe is removed.

PRESSURE VESSEL

This vessel is very similar to the vacuum vessel and is mounted on the left of the panel. This vessel is used as a pressurized vessel for the experiments in TD1004V (see Figure 1.3) The pressure vessel volume is 0.0204 m^3 .

Like the vacuum vessel, the top flange is fitted with the vacuum pressure and temperature sensors (P1 and T1).

The base flange features a pressure port that can be connected to the pressure port on the control box. This is self-sealing so it will automatically seal when the connecting pipe is removed.

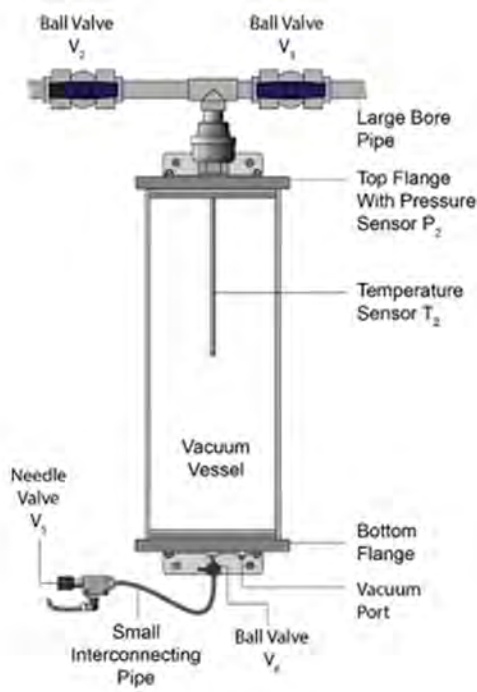


Figure 1.3: Pressure Vessel

AIR PUMP

A diaphragm pump is used to create different positive pressures in the pressure vessel. Also, to create negative pressure (i.e.: vacuum) in the vacuum vessel. To do this, the pump's discharge and suction is connected to the pressure and vacuum vessels by clear hoses.

CONTROL BOX

The TD1004V control box houses a small air pump and instrumentation for the sensors on the main unit, along with a digital, multi-line display, the control unit also includes VDAS® (see Figure 1.4).

Some experiments require fast data acquisition. For these experiments, the sensors are connected to the 'FAST' input sockets on the right of the control panel. These are then sampled directly by the integral VDAS® and displayed in the scope window of the VDAS® software. In this case, the fast inputs are not displayed locally.

The VDAS® USB port is located on the rear of the control box.

The air pump has differently sized connectors for the pressure and vacuum ports. This is to ensure the correct vessel is pressurized or vacuumed.

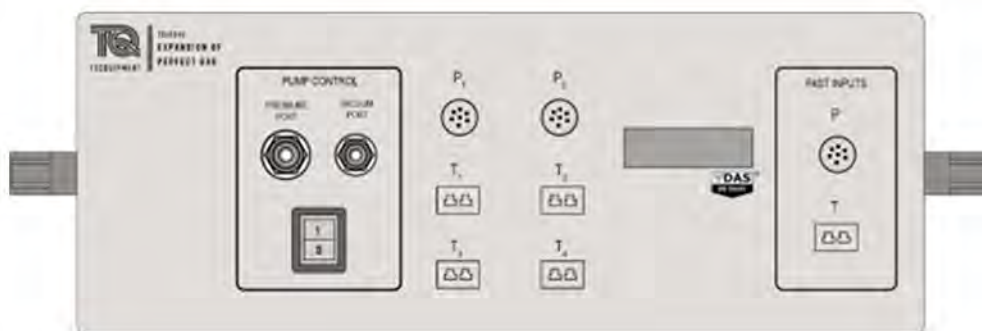


Figure 1.4: TD1004V Control Box and Air Pump

SAFETY DEVICE

The flange on the pressure vessel also holds a pressure relief valve to ensure the vessel is not over pressurized.

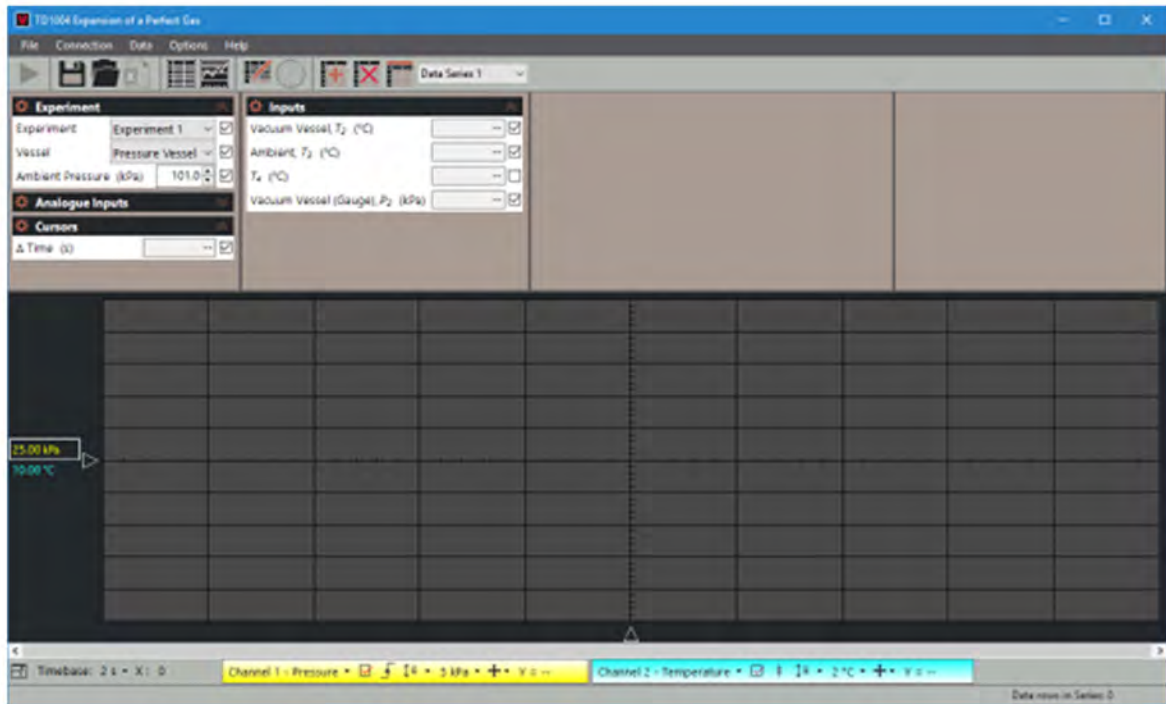
This will nominally begin to open between 0.75 and 0.85 bar gauge. If the pump is still connected, the relief valve will prevent the vessel from reaching over 1.5 bar gauge. If the valve does open, it will not close until the pressure drops below around 0.5 bar gauge due to its hysteresis.

VERSATILE DATA ACQUISITION SYSTEM (VDAS®)

The TD1004V includes integrated data acquisition hardware that allows the unit to be directly connected to a computer via a USB cable (provided with the unit) this connects via the unit control box. No additional hardware is required. TecQuipment's VDAS® software shown in Figure 1.5 is fully compatible and provides the following features:

- Automatically logs data from experiments
- Automatically calculates experiment parameters
- Saves time
- Reduces errors
- Creates charts and tables of data
- Exports data for processing in other software
- Includes Pressure-Enthalpy chart

Figure 1.5: The VDAS® software



START UP PROCEDURE

WARNING!! Do not exceed + 0.6 kPa or -0.6 bar in either vessel (± 60 kPa)

Once the unit has been connected to the mains supply:

1. If it is not already done, connect all the pressure and temperature sensors to the relevant sockets. (Check the labels on the cables and sockets).
2. Switch on the control box main switch (it is located on the back of the control box).
3. Check the LCD displays to make sure that all sensors are giving sensible readings.
4. Fully open all six valves to set the two vessels to the ambient conditions.
5. Fully close all six valves.
6. If it is not already done, connect to VDAS® and initiate communication.

SHUTDOWN PROCEDURE

1. Switch off the air pump (the switch is located on the front panel of the control box).
2. Disconnect the air hoses from the pressure and vacuum vessels.
3. Switch off the main switch (the switch is located on the back of the control box).
4. Fully open all the valves.
5. Disconnect the power supply.

THEORY

NOTATION

Table 1.1: Symbols & Nomenclature

Symbol	Definition	Units
C_p	Specific heat capacity at constant pressure	[kJ/kg-K]
C_v	Specific heat capacity at constant volume	[kJ/kg-K]
H	Enthalpy	[J]
h	Specific enthalpy	[kJ/kg]
m	Mass of substance	[g]
n	Number of moles of substance	[mol]
n	Polytropic index	-
P	Pressure	[kPa] or [bar]
P_{ABS}	Absolute pressure	[kPa] or [bar]
P_{ATM}	Atmospheric pressure	[kPa] or [bar]
P_{GAUGE}	Gauge pressure	[kPa] or [bar]
s	Specific entropy	[kJ/kg-K]
R	Ideal gas constant	[kJ/kg-K]
Q	Heat transfer rate	[kJ]
T	Temperature	[°C] or [K]
U	Internal energy	[kJ]
V	Volume	[m ³]
W	Work	[kJ]
z	Compressibility factor	-
γ	Specific heat capacity ratio	-
Subscripts		
1	State 1 (theory section)	
2	State 2 (theory section)	
<i>Initial</i>	Initial state (experiment section)	
<i>Inter.</i>	Intermediate state (experiment section)	
<i>Final</i>	Final state (experiment section)	

GAUGE AND ABSOLUTE PRESSURES

Absolute pressure (P_{ABS}) is the pressure with respect to absolute zero (a vacuum), this is normally used in calculations.

Gauge pressure (P_G) is air pressure with respect to atmospheric pressure. Zero-gauge pressure is atmospheric pressure. Gauge pressure is often used on mechanical gauges. Gauges usually show pressure in bar as it is easy to work with. These must be converted to Pascals (or $N\cdot m^{-2}$) for any calculations.

$$1 N\cdot m^{-2} = 1 Pa = 0.00001 bar$$

The TD1004V gauges and transducers measure the gauge pressure, but the calculations use absolute pressure. The following may be used to convert gauge pressure into absolute pressure.

$$P_{ABS} = P_{GAUGE} + P_{ATM}$$

IDEAL GAS AND REAL GAS

An ideal gas is one in which the molecules of gas have no volume and do not interact or collide with each other and is governed by the ideal gas equation of state as follows:

$$PV = nRT \quad (1.1)$$

$$U = nC_v T \quad (1.2)$$

A real gas is one in which the molecules of gas have a finite volume and velocity (i.e. real volume) and interacts with other molecules in gas (i.e. inter-molecular forces) when pressure increases. The gas is governed by the real gas equation of state as follows:

$$PV = znRT \quad (1.3)$$

The difference between the ideal and real gas equation of state is the compressibility factor z , this is often called the gas deviation factor from the ideal gas.

Table 1.2: Compressibility Factor of Real Gas

Pressure	Compressibility Factor	Features
Low	$z = 1$	No inter-molecular forces, like ideal gas behavior
Moderate	$z < 1$	Gas occupies less volume; attractive forces occur between molecules
High	$z > 1$	Gas is compressed, repulsive forces are dominant

As seen from Figure 1.6, the relationship between compressibility, pressure and temperature is explained as follows:

- $z \rightarrow 1$ when $P \rightarrow 0$ for all T shown. The air has ideal gas behavior at very low pressure.
- $z \approx 1$ when $P < 300$ kPa, for all T shown. The air can be considered to behave closely enough to an ideal gas under these pressures.
- $z < 1$ when $P \approx 300 \rightarrow (10000)$ kPa, for all T shown.
- $z > 1$ when $P > 10000$ kPa, for most T shown.

Thus, the ambient air can be considered an ideal gas at low pressures and the ideal gas law can be used.

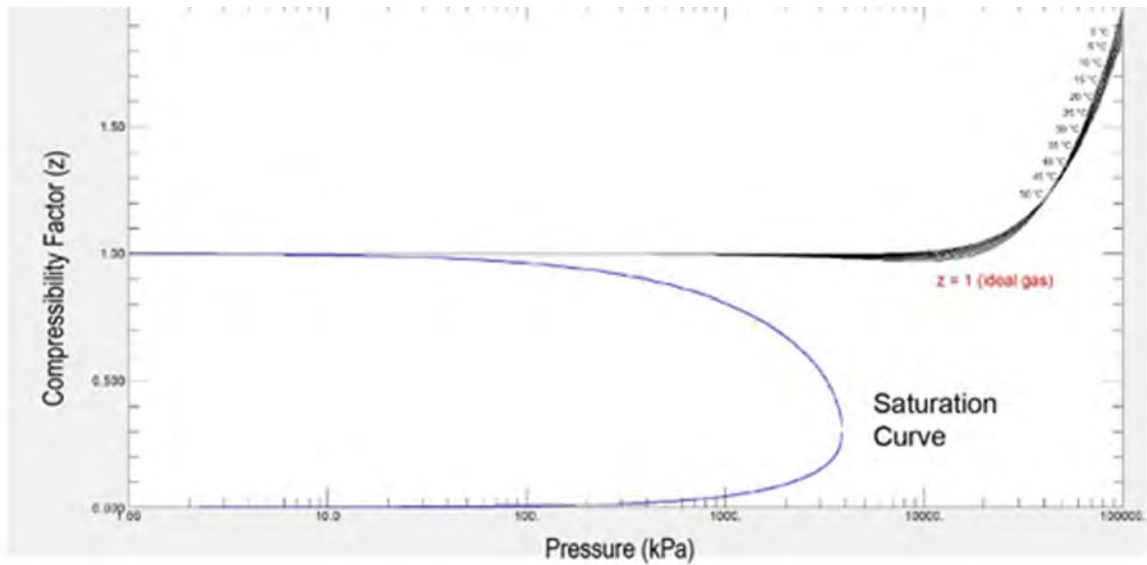


Figure 1.6: Relationship of Air Compressibility factor with Pressure and Temperature

SPECIFIC HEAT CAPACITY

The specific heat capacity, of a substance is the amount of heat energy required to raise the temperature of a unit mass of the substance by one degree [J/kg-K]:

There are two common specific heat quantities based on the conditions during which the heating process is carried out, constant volume and constant pressure.

SPECIFIC HEAT CAPACITY AT CONSTANT VOLUME

Heat energy is added at constant volume that goes into the increase in internal energy of gas. According

$$C = \frac{1}{m} \frac{\delta Q}{\delta T}$$

to the first law of thermodynamic under isochoric change, $\delta Q = dU$ thus:

Due to

Thus:

$$C_v = \frac{1}{m} \frac{\partial U}{\partial T}$$

SPECIFIC HEAT CAPACITY AT CONSTANT PRESSURE

$$u = \frac{U}{m}$$

Heat energy is added at a constant pressure that causes gas to expand, expanding the container.

$$C_p = \frac{\partial u}{\partial T}$$

According to the first law of thermodynamics under an isobaric change, $\delta Q = dH$ thus:

Due to

$$C_p = \frac{1}{m} \frac{\partial H}{\partial T}$$

Thus:

$$h = \frac{H}{m}$$

For an ideal gas, the difference between C_p and C_v is determined based on the equation of enthalpy

$$C_p = \frac{\partial h}{\partial T}$$

definition and the ideal gas equation of state as follows:

$$H=U+PV \quad (1.4)$$

$$PV=RT \quad (1.5)$$

Combine Equations 1.4 and 1.5

$$H=U+RT$$

The ratio of specific heat capacities at constant pressure and volume is called the “specific heat ratio” and

$$\frac{dH}{dT} = \frac{dU}{dT} + R$$

$$R = \frac{dH}{dT} - \frac{dU}{dT} = C_p - C_v$$

can be determined if C_v is known:

$$\gamma = \frac{C_p}{C_v} = 1 + \frac{R}{C_v} \quad (1.6)$$

Figure 1.7 illustrates the relationship between the ratio of specific heat capacities and the temperature of the ambient air under atmospheric pressure ($P_{\text{ATM}} = 101.325 \text{ kPa}$). For an ideal gas, increasing temperature enables vibrational degrees of freedom, so that C_v increases. Thus, the specific heat capacity ratio increases as explained from Equation 1.6.

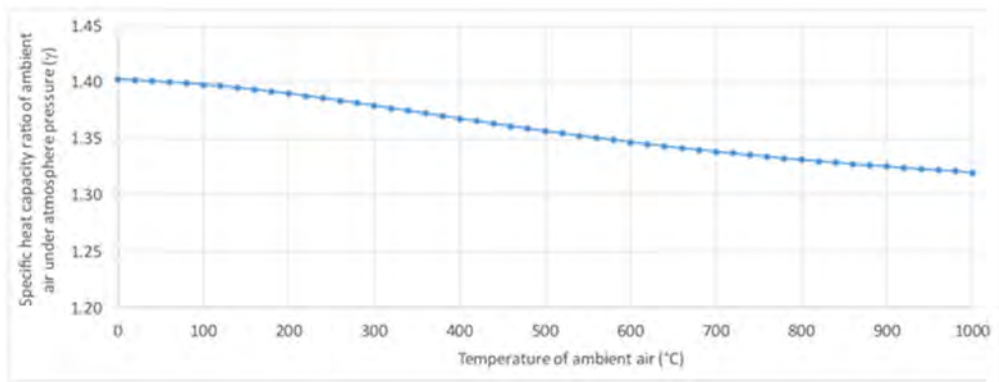


Figure 1.7: Relationship Between Specific Heat Ratio and Temperature for Ambient Air

Note... for comparison purposes of the experimental results, the reference value of the specific heat capacity ratio for air is $\gamma = 1.401$ under room temperature.

ISOTHERMAL, ADIABATIC AND POLYTROPIC PROCESSES

An **isothermal process** is a thermodynamic process that a substance undergoes without a change in its temperature. As the temperature remains unchanged during this process, the change in internal

energy is zero ($dU = 0$). Applying the first law of thermodynamics this gives:

$$dU = dQ + dW = C_v dT = 0$$

or

$$dQ = -dW$$

Thus, in an **isothermal expansion**, the heat absorbed by the gas equals the work done by the ideal gas on its surroundings. Applying the ideal gas law, an isothermal process "1 – 2" is given by:

$$P_1 V_1 = P_2 V_2 \quad \text{or} \quad \frac{P_1}{P_2} = \frac{V_2}{V_1}$$

An **adiabatic process**, is a thermodynamic process in which there is no heat energy transfer from or to the substance across the system boundary ($dQ = 0$). Applying the first law of thermodynamics gives:

$$dU = -dW \quad \text{"or"} \quad \Delta U = -W$$

For an adiabatic process “1 – 2”, the above equation becomes

$$U_2 - U_1 = -W$$

$$mC_v (T_2 - T_1) = \frac{P_1 V_1 - P_2 V_2}{n - 1} = -\frac{mR(T_1 - T_2)}{n - 1}$$

$$\frac{R(T_2 - T_1)}{n - 1} = C_v (T_2 - T_1)$$

$$C_v = \frac{R}{n - 1} = \frac{C_p - C_v}{n - 1}$$

or

$$n = \frac{C_p}{C_v}$$

Thus, an adiabatic process of a gas has an index n which equals specific heat ratio γ :

$$\gamma = n = \frac{C_p}{C_v}$$

Applying the ideal gas law, an adiabatic process “1 – 2 “ is given by

$$P_1 V_1^\gamma = P_2 V_2^\gamma \text{ or } \frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^\gamma$$

A **polytropic process** is a thermodynamic process taking place in a manner that obeys the relationship below:

$$PV^n = \text{constant}$$

where, n is polytropic index, which is any real number depending on the particular process the substance undergoes.

- When $n = 0$, $P = \text{constant}$, the process is at constant pressure and called an **isobaric process**.
- When $n = 1$, $PV = \text{constant}$, the process is at a constant temperature and called an **isothermal process**.
- When $n = \gamma$, $PV^\gamma = \text{constant}$, the process has no heat exchange and is called an **adiabatic process**.
- When $n = \infty$, $PV^\infty = \text{constant}$, the process is at constant volume and is called an **isochoric process**.

Thus, the polytropic process is a general classification of particular processes which are commonly seen in practice. They are summarized on the pressure / volume chart as can be seen in Figure 1.8 below.

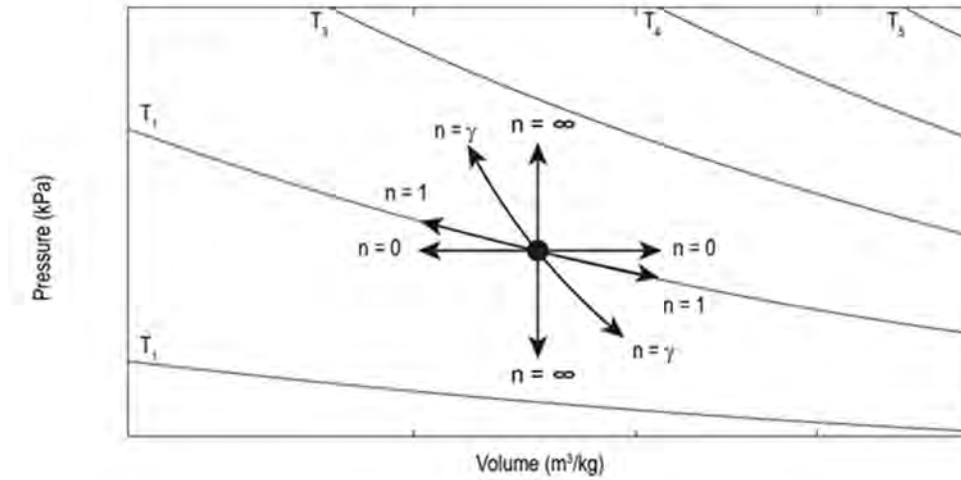


Figure 1.8: Particular Polytropic Processes on a Pressure / Volume Chart

REVERSIBLE, IRREVERSIBLE, AND ISENTROPIC PROCESSES

A **reversible process** is a process for which its reversal can take place to bring the system from the final state back to the original state without leaving any trace on the surroundings. It means that the system and surroundings can be restored to their initial states by reversing the direction of the process without a change in the magnitude of the work done or the heat exchanged.

An **irreversible process** is a process which is either not reversible or if it is, it results in changes in the thermodynamic properties of the system and surroundings. Most real processes are irreversible.

The second law of thermodynamics can be used to determine if a process is reversible or irreversible via a change in entropy “ ds ”.

$$ds = \frac{\delta Q}{T}$$

If a process occurs in which the entropy is unchanged in the forward direction, the backward direction will also exhibit an unchanged entropy. Such a process is called a reversible process. Entropy is neither created nor destroyed during this process.

If the entropy is changed in the forward direction, the backward direction of the process is therefore impossible. Such a process is called an irreversible process.

The change in entropy of an ideal gas can be calculated using the following equation:

$$s_2 - s_1 = C_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{V_2}{V_1}\right) \quad (1.7)$$

For a reversible adiabatic process, the following relationship can be used

$$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1} \quad (1.8)$$

Substitute Equation 1.8 into Equation 1.7, the change in entropy is:

$$s_2 - s_1 = C_v \ln \left(\frac{V_2}{V_1} \right) + R \ln \left(\frac{V_2}{V_1} \right)$$
$$s_2 - s_1 = \left[R - C_v \left(\frac{C_p}{C_v} - 1 \right) \right] \ln \left(\frac{V_2}{V_1} \right) = 0$$

Thus, entropy change for a reversible adiabatic process is always zero.

An **isentropic process** is a process in which the entropy is constant during the process ($\Delta s = 0$). If combining the first law of thermodynamics and the second law of thermodynamics together, we arrive at the following equation:

$$\frac{P_2 V_2^\gamma}{P_1 V_1^\gamma} = e^{\frac{\Delta s}{C_v}}$$

As $\Delta s \rightarrow 0$, $PV^\gamma = \text{constant}$, this is an adiabatic process. Thus, an isentropic process is always a reversible adiabatic process.

$$\text{isentropic} = \text{adiabatic} + \text{reversible}$$

An adiabatic process can be either reversible or irreversible, thus the entropy can change or remain constant during the process.

CONSTANT INTERNAL ENERGY PROCESS

A process in which the internal energy remains constant is called a “constant internal energy process”.

$$\Delta U = 0$$

The first law of thermodynamics becomes

$$\Delta U = Q - W = 0$$

Thus, to enable the internal energy to be unchanged ($\Delta U = 0$), $Q = 0$ and ($W = 0$) or $Q = W$. The unit can demonstrate this process by an adiabatic expansion from a high pressure to a vacuum pressure. This is a free expansion process which has no work done ($W = 0$) it is also an adiabatic process ($Q = 0$).

REVERSIBLE ADIABATIC AND CONSTANT VOLUME PROCESS (CLÉMENT DESORMES METHOD)

The method uses two consecutive thermodynamic processes during air expansion from a high pressure to a lower pressure to calculate specific heat capacity ratio of the air.

1. Reversible adiabatic process from the initial state ($P_{INITIAL}, V_{INITIAL}, T_{INITIAL}$) to the intermediate state ($P_{INTER}, V_{INTER}, T_{INTER}$).
2. Constant volume process from the intermediate pressure ($P_{INITIAL}, V_{INITIAL}, T_{INITIAL}$) to the final pressure ($P_{FINAL}, V_{FINAL} = V_{INTER}, T_{FINAL} = T_{INTER}$).

For these processes, we need a system of gas that has a valve to allow it to expand. If the gas is at a higher pressure than its surroundings initially it will expand out when the valve is opened. During this step, the volume of the gas increases as the gas pressure reduces. At some intermediate point, the valve is closed, then the volume can no longer expand. When the gas settles at its final state, the pressure is higher than the intermediate value. These two processes are represented in the P-V chart (Figure 1.9).

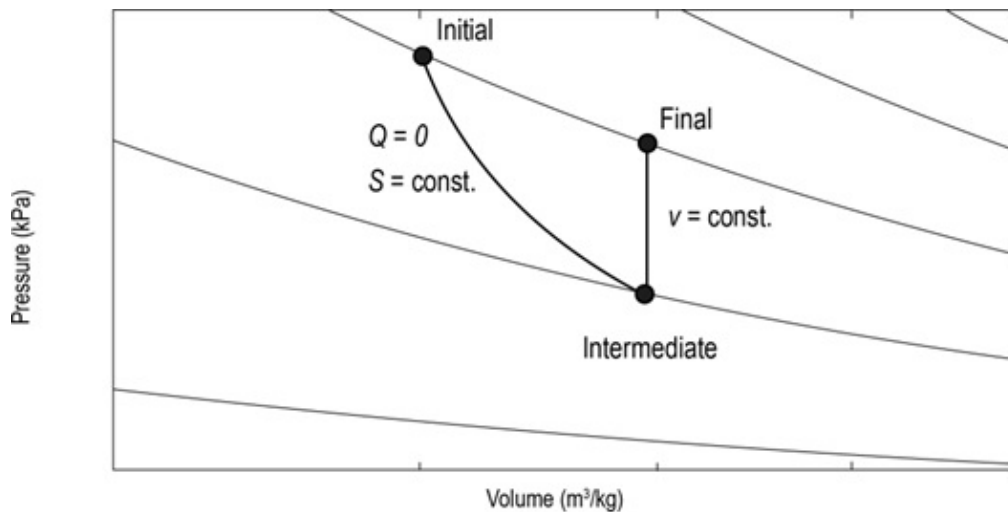


Figure 1.9: Adiabatic and Isochoric Processes on P-V Chart

We can combine the first law of thermodynamics with our definitions of C_v and C_p to determine an expression for γ in terms of the pressures in Figure 1.9.

Beginning with the First Law of Thermodynamics

$$dQ = dU + dW$$

For a reversible adiabatic process, $dQ = 0$.

or

$$dU = -dW = -PdV$$

At constant volume, heat capacity relates change of internal energy to change of temperature.

$$C_v = \frac{dU}{dT} \text{ or } dU = C_v dT$$

Thus

$$C_v dT = -PdV \quad (1.9)$$

From ideal gas law,

$$PV = RT$$

Alternatively,

$$PdV + VdP = RdT \quad (1.10)$$

Substitute dT from Equation 1.9 to Equation 1.10

$$\begin{aligned} \frac{C_v}{R}(PdV + VdP) &= -PdV \\ P\left(\frac{C_v}{R} + 1\right)dV &= -\frac{C_v}{R}VdP \\ \frac{dP}{P}\left(\frac{C_v + R}{C_v}\right)\frac{dV}{V} &= -\frac{C_p}{C_v}\frac{dV}{V} \end{aligned} \quad (1.11)$$

Integrating both sides of Equation 1.11 for the adiabatic process:

$$\ln \frac{P_{INTER}}{P_{INITIAL}} = -\frac{C_p}{C_v} \ln \frac{V_{INTER}}{V_{INITIAL}} = \frac{C_p}{C_v} \ln \frac{V_{INITIAL}}{V_{INTER}}$$

Now determining specific heat capacity ($\gamma = C_p / C_v$) via measured quantities of pressure using the constant volume process from the intermediate state to the final state (i.e.: $V_{FINAL} = V_{INTER}$; $T_{FINAL} = T_{INTER}$).

$$\frac{P_{INITIAL} V_{INITIAL}}{RT_{INITIAL}} = \frac{P_{FINAL} V_{FINAL}}{RT_{FINAL}}$$

$$\frac{P_{FINAL}}{P_{INITIAL}} = \frac{V_{INITIAL}}{V_{FINAL}} = \frac{V_{INITIAL}}{V_{INTER}} \quad (1.12)$$

Substitute Equation 1.9 into Equation 1.8

$$\gamma = \frac{C_p}{C_v} = \frac{\ln \frac{P_{INTER}}{P_{INITIAL}}}{\ln \frac{V_{INITIAL}}{V_{INTER}}} = \frac{\ln \frac{P_{INTER}}{P_{INITIAL}}}{\ln \frac{P_{FINAL}}{P_{INITIAL}}}$$

Therefore,

$$\gamma_{rev} = \frac{\ln P_{INTER} - \ln P_{INITIAL}}{\ln P_{FINAL} - \ln P_{INITIAL}} \quad (1.13)$$

IRREVERSIBLE ADIABATIC PROCESS

The argument has risen that the expansion as mentioned in the Clément Desormes method is not a reversible adiabatic process (i.e.: not an isentropic process) due to possible change in entropy ($q = 0$ but $ds \neq 0$) as the result of adiabatic expansion against a constant atmospheric pressure P_{ATM} . Thus, Equation 1.9 becomes

$$C_v dT = -P_{ATM} dV \quad (1.14)$$

From the

ideal gas law, $V = RT/P$ and $C_p - C_v = R$ are substituted in Equation 1.14 after integration becomes

$$C_v \frac{P_{ATM} - P_{INITIAL}}{P_{INITIAL}} = -C_p \left(\frac{P_{ATM}}{P_{INITIAL}} - \frac{T_{INTER}}{T_{INITIAL}} \right) \quad (1.15)$$

The intermediate temperature is calculated from the constant volume process

$$\frac{T_{INTER}}{P_{ATM}} = \frac{T_{FINAL}}{P_{FINAL}} \quad (1.16)$$

Re-arranging Equations 1.15 and 1.16, the ratio of specific heat for an irreversible adiabatic process is calculated as follows

$$\gamma_{irrev} = \frac{\frac{P_{INITIAL}}{P_{ATM}} - 1}{\frac{P_{INITIAL}}{P_{FINAL}} - 1} \quad (1.17)$$

If the results derived from Equations 1.13 for γ_{rev} and 1.17 for γ_{irrev} are not much different, the assumption of a reversible adiabatic process for the air expansion in Exercise A is acceptable.

USING ISOTHERMAL PROCESS TO DETERMINE THE VOLUME RATIO

A vessel of high pressure undergoes an isothermal expansion into a second vessel at an initial lower starting pressure, we can use the pressure and temperatures before and after to determine the volume ratio of the two vessels.

Using the isothermal expansion process from the initial state of vessel 1 (P_1, V_1, T_1) and vessel 2 (P_2, V_2, T_2) to the final state of interconnection vessel ($P_{FINAL}, V_{FINAL}, T_{FINAL}$).

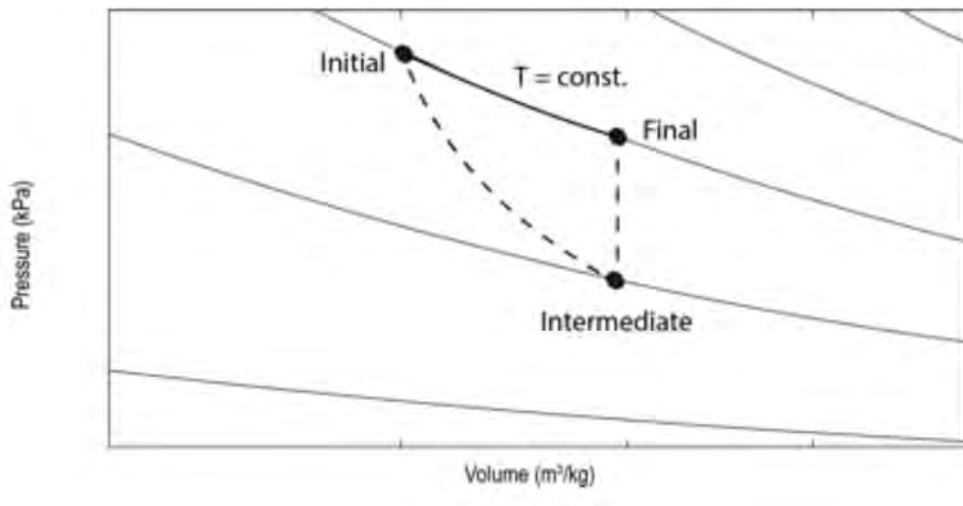


Figure 1.10: Isothermal Processes on P-V Chart

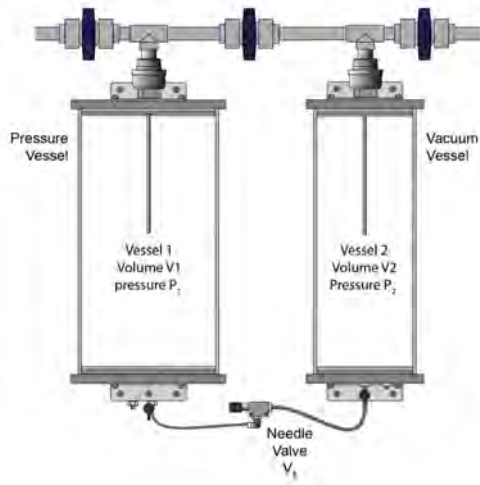


Figure 1.11: Isothermal Process

Assuming the initial temperature of the two vessels is the same as the ambient temperature and the temperature is unchanged during expansion due to isothermal process

$$T_1 = T_2 = T_{FINAL} = T$$

The final mass and volume of the air after the expansion process is:

$$m_{FINAL} = m_1 + m_2$$

$$V_{FINAL} = V_1 + V_2$$

$$P_{FINAL} = P_f$$

From the ideal gas law,

$$P_1 V_1 = m_1 R T \quad \text{or} \quad m_1 = \frac{P_1 V_1}{R T} \tag{1.18}$$

$$P_2 V_2 = m_2 R T \quad \text{or} \quad m_2 = \frac{P_2 V_2}{R T} \tag{1.19}$$

$$P_f (V_1 + V_2) = (m_1 + m_2) R T \tag{1.20}$$

Substitute Equations 1.18 and 1.19 into Equation 1.20,

$$P_f (V_1 + V_2) = \left(\frac{P_1 V_1}{R T} + \frac{P_2 V_2}{R T} \right) R T \tag{1.21}$$

Divide both sides by V_2

$$P_f \frac{V_1}{V_2} + P_f = P_1 \frac{V_1}{V_2} + P_2$$

$$\frac{V_1}{V_2} = \frac{P_f - P_2}{P_1 - P_f} \quad (1.22)$$

REFERENCES

- TecQuipment, TD1004V Expansion of a Perfect Gas User Guide, 2017.

EXPERIMENTS

GENERAL

Refer to Figure 1.12 below for a key as to which valve is which and how to operate them.

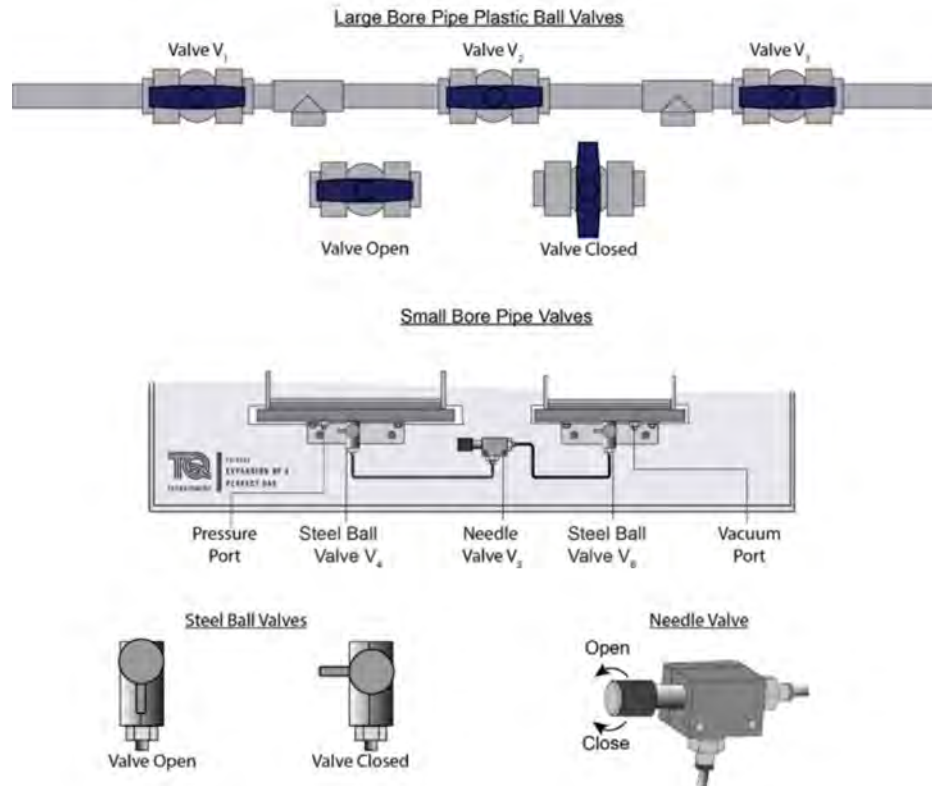


Figure 1.12: Valves

SAFETY

- For sound pressure levels above 85 dB (A) it is a requirement that ear defenders are worn.
- Do not leave the apparatus under pressure or vacuum when it is not in use, as this may cause long term damage to the acrylic vessels.
- Turn off air pump when not in use.
- Do not exceed maximum air pressure of 0.6 bar gauge. Do not exceed minimum air pressure of -0.6 bar gauge.

EXPERIMENT 1 - DEMONSTRATION OF PRESSURE AND TEMPERATURE SENSOR RESPONSE DURING A BRIEF DE-PRESSURIZATION

AIM

To assess and compare the responses of the pressure and temperature sensors during a brief de-pressurization.

PROCEDURE

1. Follow the start-up procedure (see page 7).
2. Select Experiment 1 from the experiment drop down in the VDAS® software.
3. Select the pressure vessel from the vessel drop down in the VDAS® software.
4. Enter the ambient pressure in the VDAS® software.
5. Start VDAS® communications.
6. Connect pressure connection P_1 (from the large vessel) to the fast input pressure port on the control box P.
7. Connect the pressure port on the control box to the pressure port on the pressure vessel.
8. Switch the air pump ON to pressurize the large vessel.
9. Wait until the pressure of the large vessel reaches about 0.3 bar ($30 \text{ kPa} \pm 0.5 \text{ kPa}$).
10. Turn the air pump OFF.
11. Disconnect the hose from the pressure port on the pressure vessel.
12. Monitor the pressure and temperature of the air inside the large vessel until they are stabilized (wait a minute or two until T_1 matches ambient temperature $T_3 \pm 0.3^\circ\text{C}$).
13. Move T_1 thermocouple cable to the fast input port T on the control box.
14. Open valve V_1 and quickly close it for a part of air volume in the large vessel to expand to the atmosphere pressure.
15. Monitor the pressure and temperature of the large vessel until they are stabilized.
16. Stop the communications to scroll through the recorded data. Click the shift trace icon for each channel to offset each trace to get a better view. Right click on the trace screen and select "Save analogue traces to File". Save file to the appropriate Documents directory by clicking the TD1004 folder and your registered Lab Section sub folder. By default the file is called "VDAS_Traces.jpg". Note the vertical scale divisions for each trace which will normally be 10 kPa and 5°C after shifting and offsetting.
17. Copy the trace file to a USB flash drive to be used for the lab report.
18. Open V_1 to allow the vessel to de-pressurize.

DISCUSSION

Show and compare the two traces and discuss any differences.

EXPERIMENT 2 - DETERMINATION OF SPECIFIC HEAT CAPACITY RATIO UNDER REVERSIBLE ADIABATIC (I.E.: ISENTROPIC) PROCESS

AIM

To determine the specific heat capacity ratio of ambient air directly from measurements of pressure during a reversible adiabatic expansion process using the method named Clément Desormes.

PROCEDURE

1. Follow the start-up procedure (see page 7).
2. Connect sensor P_1 to the fast input socket on the control box. Move T_1 thermocouple cable to the regular input port T_1 on the control box.
3. Select Experiment 2 from the experiment drop down in the VDAS® software.
4. Select the pressure vessel from the vessel drop down in the VDAS® software.
5. Enter the ambient pressure in the VDAS® software. Record the value on the data sheet.
6. Start VDAS® communications.
7. Connect the pressure port on the control box to the pressure port on the pressure vessel.
8. Switch the air pump ON to pressurize the large vessel.
9. Wait until the pressure of the large vessel reaching about 0.3 bar ($30 \text{ kPa} \pm 0.5 \text{ kPa}$).
10. Turn the air pump OFF.
11. Disconnect the hose from the pressure port on the pressure vessel.
12. Monitor the pressure and temperature of the air inside the large vessel until they are stabilized (wait until T_1 matches ambient temperature $T_3 \pm 0.5^\circ\text{C}$).
13. Record the initial pressure P_{INITIAL} of the large vessel and ambient pressure and enter the value on the data sheet..
- 14. Quickly, open the valve V_1 and quickly close it** for a part of air volume in the large vessel to expand.
15. Monitor the pressure drop during opening and closing the valve V_1 . Stop the VDAS® communications and scroll the scope window to view the pressure drop. Click the shift trace icon for the pressure channel below to offset to get a better view of the trace.
16. Measure and record the minimum pressure P_{INTER} (the lowest pressure recorded) on the data sheet before it recovers (Figure 1.13).
17. Restart the VDAS® communications.
18. Monitor the pressure and temperature of the large vessel until they are stabilized.
19. Wait until the temperature of the large vessel returns to the ambient temperature (T_1 matches $T_3 \pm 0.5^\circ\text{C}$).
20. Record the final pressures P_{FINAL} of the large vessel and ambient pressure and temperature.

21. Open V_1 to de-pressurize the vessel.
22. Repeat the same experiment and vary the pressure to 0.4 bar, 0.5 bar and 0.6 bar.
23. Repeat the same experiment three times to ensure the repeatability and reproducibility of the experimental results.

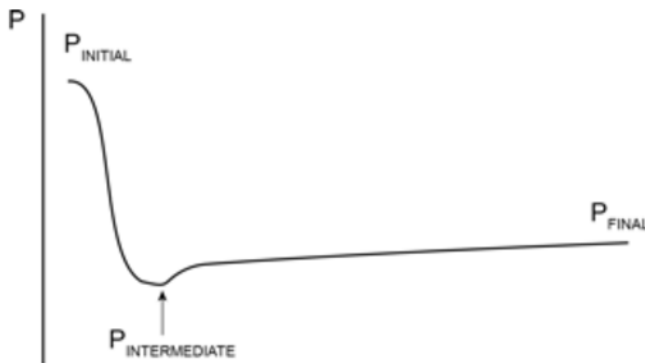


Figure 1.13: Chart Showing Positions of P_{INITIAL} , $P_{\text{INTERMEDIATE}}$ and P_{FINAL}

RESULTS/DISCUSSION

1. Convert the measured values into absolute pressure values P_{ABS} .
2. Calculate the mean specific heat capacity ratio of the air for the different pressures using Equation 1.13 based on the three trial results..

Some points to consider for your discussion of Experiment 2.

1. Compare the calculated ratio of specific heat capacities with the standard value of air and comment how representative the experiment result is?
2. Why is the process of air expansion as conducted in this exercise considered an adiabatic process?

EXPERIMENT 3 - DETERMINATION OF SPECIFIC HEAT CAPACITY RATIO UNDER IRREVERSIBLE ADIABATIC PROCESS

AIM

To determine specific heat capacity ratio of air directly from measurements of pressure during an irreversible adiabatic expansion process.

PROCEDURE

1. Follow the start-up procedure (see page 7).
2. Connect sensor P_1 to the fast input socket on the control box.
3. Select Experiment 3 from the experiment drop down in the VDAS® software.
4. Select the pressure vessel from the vessel drop down in the VDAS® software.
5. Enter the ambient pressure in the VDAS® software. Record the value on the data sheet.
6. Start VDAS® communications.
7. Check pressures on the display to make sure that both vessels are under atmosphere pressure.
8. Close all ball valves.
9. Connect the pressure port on the control box to the pressure port on the pressure vessel.
10. Switch the air pump ON to pressurize the large vessel.
11. Wait until the pressure of the large vessel reaches about 0.3 bar (30 kPa \pm 0.5 kPa).
12. Turn the air pump OFF.
13. Disconnect the hose from the pressure port on the pressure vessel.
14. Monitor the pressure and temperature of the air inside the large vessel until they are stabilized. Wait until T_1 matches ambient temperature $T_3 \pm 0.5^\circ\text{C}$.
15. Record the initial pressure P_{INITIAL} of the large vessel and enter the value on the data sheet.
16. Quickly, **fully open the valve V_1 and close it after 1-2 seconds** for the pressure to reach atmospheric pressure.
17. Monitor the pressure and temperature of the large vessel until they are stabilized.
18. Wait until the temperature of the large vessel returns to the ambient temperature (wait until T_1 matches ambient temperature $T_3 \pm 0.5^\circ\text{C}$).
19. Record the final pressure P_{FINAL} of the large vessel and the value on the data sheet.

RESULTS AND DISCUSSION

1. Convert the measured values into absolute pressure values P_{ABS} .
2. Calculate the mean specific heat capacity ratio of the air using Equation 1.17 for the three trials.

Some points to consider for your discussion of Experiment 3.

1. Compare the calculated ratio of specific heat capacities with the result obtained in Experiment 2 (0.3 bar starting pressure only) and comment how different the two results are?
2. Why is the process of air expansion as conducted in this experiment still considered a reversible process rather than an irreversible process?

DATA SHEET

LAB 1: EXPANSION OF A PERFECT GAS

EXPERIMENT 1

Bring a USB flash drive and copy trace picture file from desktop computer.

EXPERIMENT 2

Ambient Pressure [inches Hg]: _____

	0.3 bar			0.4 bar			0.5 bar			0.6 bar		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
P_{INITIAL} [kPa]												
P_{INTER} [kPa]												
P_{FINAL} [kPa]												

EXPERIMENT 3

Ambient Pressure [inches Hg]: _____

	0.3 bar		
	Trial 1	Trial 2	Trial 3
P_{INITIAL} [kPa]			
P_{INTER} [kPa]			
P_{FINAL} [kPa]			



LAB

2

DWSIM

INTRODUCTION

DWSIM is an open-source simulation software allowing the simulation of complex thermodynamic cycles. It is user-friendly and allows the determination of characteristics of several simple to complex cycles: net work, heat input, etc. These instructions were prepared with version 8.0.4. There may be minor differences with newer versions, but the same operations are possible.

GETTING STARTED

We would like to outline the steps involved in setting up a typical Rankine cycle, which is a very common ideal steam power cycle (See Figure 2.1). Using DWSIM, setting up such a cycle is actually very simple, but it requires that we know some of the basic facts and typical assumptions that apply to the cycle. We will examine a typical Rankine cycle problem and note the assumptions necessary to find the problem's solution, many of which will not be stated explicitly in the problem.

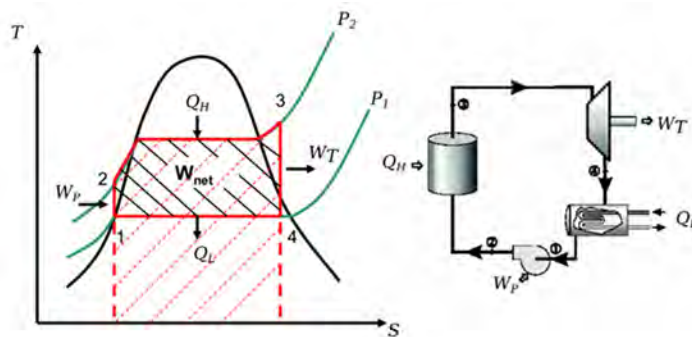


Figure 2.1: Ideal Rankine Cycle

TYPICAL PROBLEM

Let's say we want to set up a typical Rankine Cycle. A typical problem statement is:

Consider an ideal steam cycle in which steam enters the turbine at 5MPa, 400°C, and exits at 10kPa.

Calculate the **thermal efficiency** and the **net work per kilogram of steam**.

This may not sound like a very complete problem description, since we are given only three numbers. However, it is sufficiently described that we can solve it. In the next section, we will detail the other properties of a Rankine cycle which will allow us to complete its design.

WHAT IT LOOKS LIKE

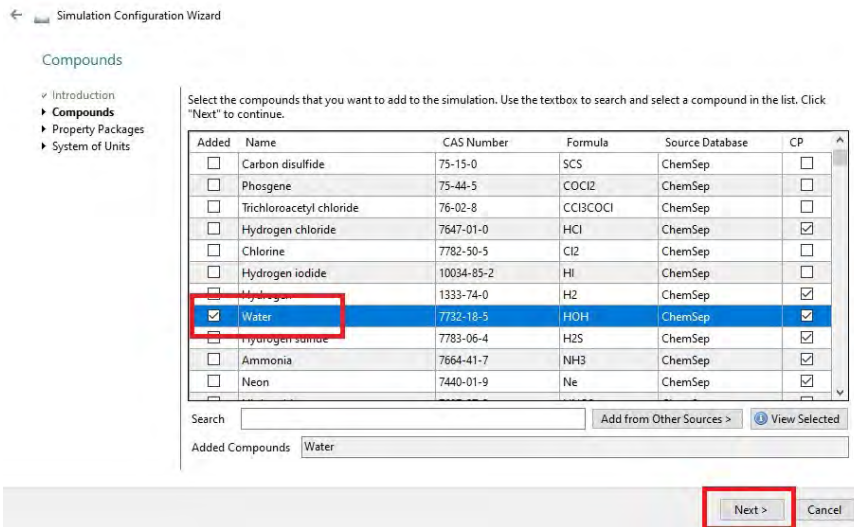
First, an "ideal steam cycle" where we are only told of one turbine is probably a Rankine cycle. This cycle consists of a heater, a turbine, a cooler (or "condenser"), and a pump, in that order. We will talk about the properties of each component and the state points between them later.

FIRST STEPS

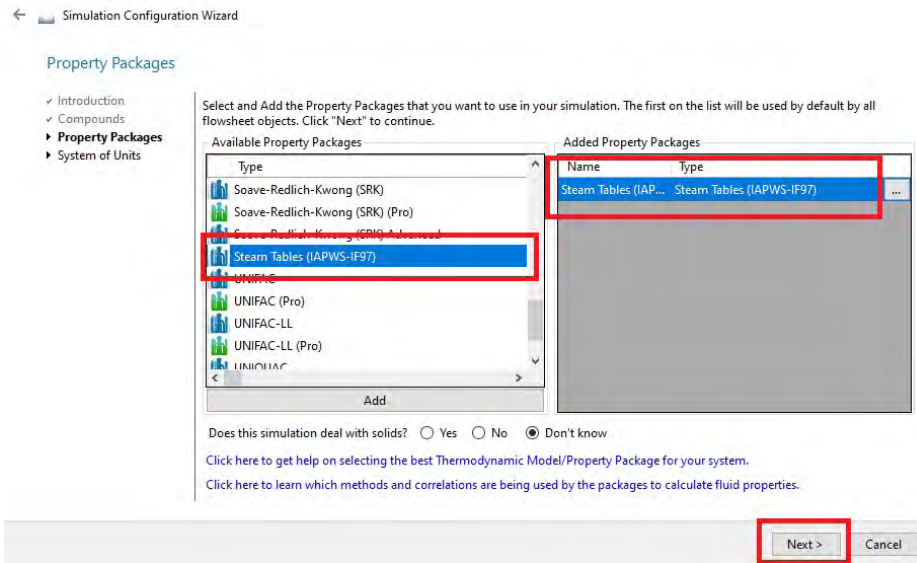
We will first open the software and select a new steady state simulation as shown in the image below. A Simulation Configuration Wizard will open up. Click Next to continue.



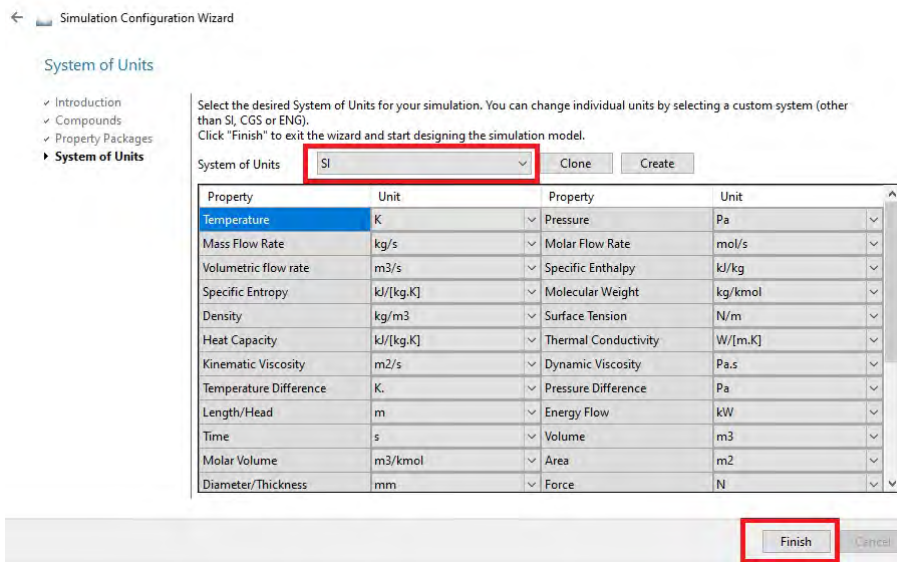
The next step consists of choosing the compounds that will be used in the simulation. In our case, it's water. Check the box for water and then click Next.



The next page shows different property packages that can be used in the simulation. Scroll and double click "Steam Tables" package from the Available Property Packages dialog box on the left. Make sure the selected package is visible in the Added Property Packages on the right. Then click "Next".



Finally, select the SI Unit system and click Finish.



Based on our selection of compound and the conditions we set at the inlet or outlet of each component, DWSIM will calculate the remaining intensive values by using Steam Tables as a library. DWSIM can save us much time in table lookups, especially when a state point would require interpolation to find.

ANALYZING OUR DESIGN

For this example, we will add one component at a time while considering the assumptions which allow DWSIM to solve the cycle. It is particularly during this stage that our own knowledge of thermodynamics is critical to making assumptions DWSIM will use in design solution.

We start at the heater.

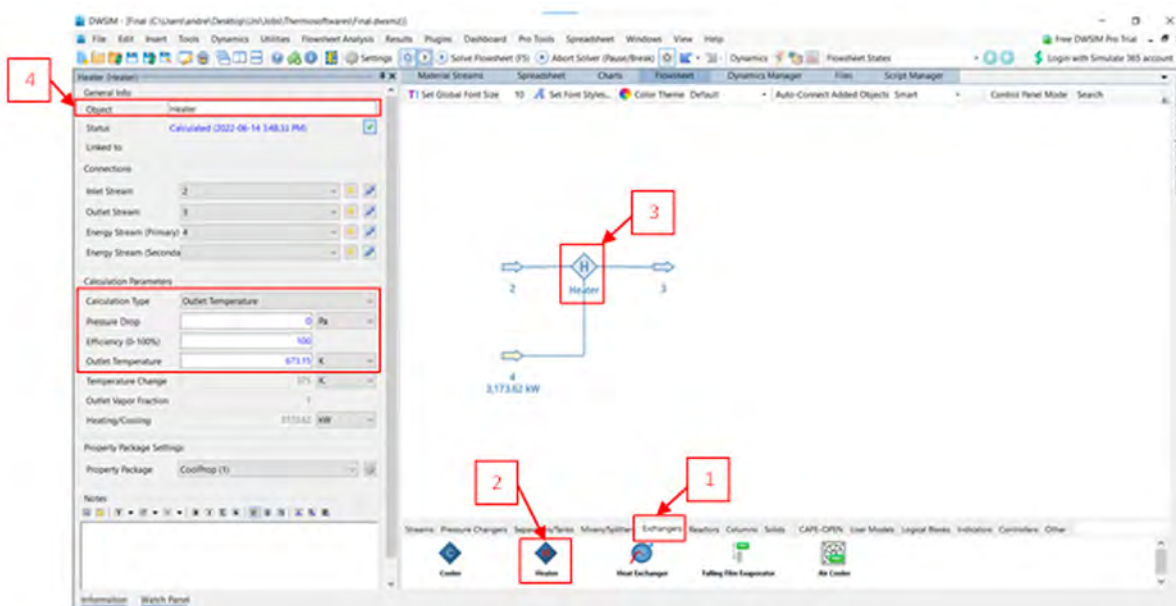
THE HEATER

We aren't explicitly told anything about the heater, so we assume the Rankine cycle has ideal components. Heaters are usually a long series of tubes through which the working fluid is forced. As it moves through the tubes, heat (from a combustion process, for instance) is applied to the outside of the tubes and the working fluid gains enthalpy. In real heaters, it takes energy to push the fluid through all of these tubes and there is a pressure loss for the process. In an ideal heater, we assume that this pressure loss is negligible, and the heater is isobaric. Hence, when we consider non-ideal components, we are often given a pressure loss (or a relation that allows us to compute a pressure loss for the heater).

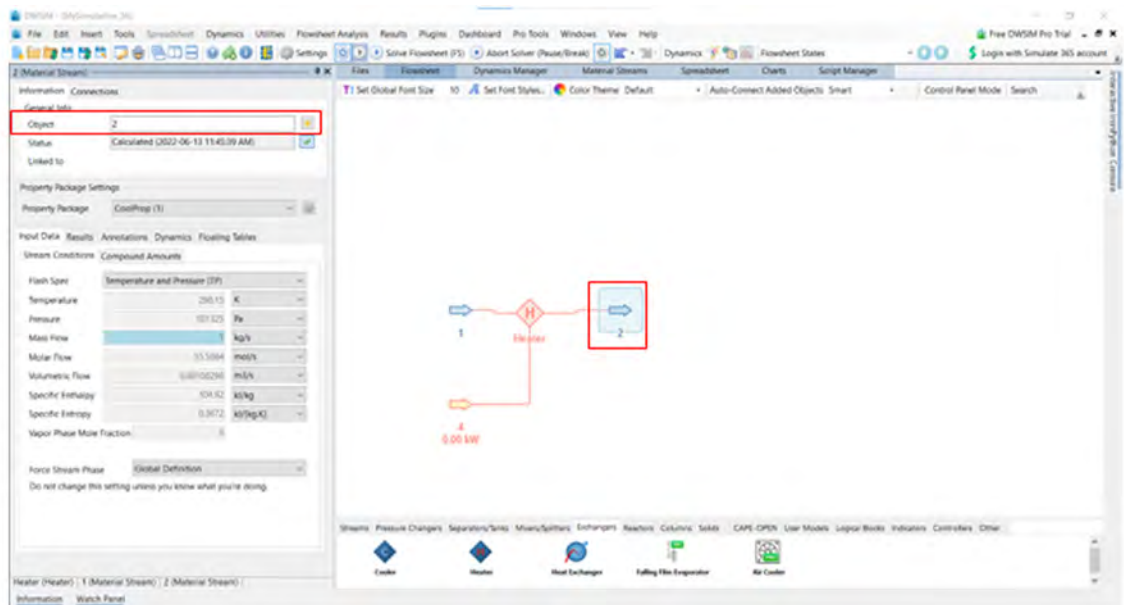
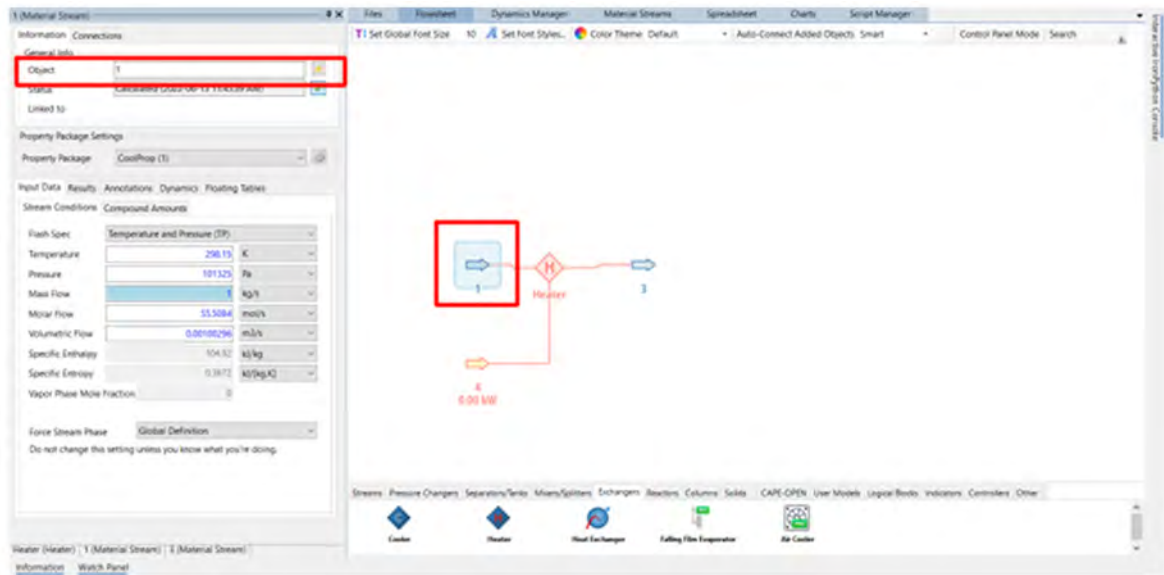
In DWSIM, first select Exchangers in the bottom tab of the screen, then select the Heater and drag it to the flowsheet (in the middle of your screen).

Now, click on your inserted Heater:

- Change the Object name to “Heater”.
- Set Calculation Type to Outlet Temperature and set the Outlet Temperature to 400°C.
- Set the Pressure Drop to 0 and the Efficiency to 100%. This corresponds to an ideal heater.



In the next steps, we'll just rename the arrows for the inlet and outlet of the heater. First click on the inlet arrow and change the Object to 1, then select the outlet arrow and change the Object to 2.



THE TURBINE

The next component is the turbine. As we aren't told anything explicitly about this turbine, we assume ideality. In general, this means it is adiabatic (no heat transfer) and reversible (no losses) and hence isentropic (zero change in entropy). Even if we did not know that it was ideal, we would probably assume it to be adiabatic because we have not been told how much heat transfer takes place and we have no way to figure it out.

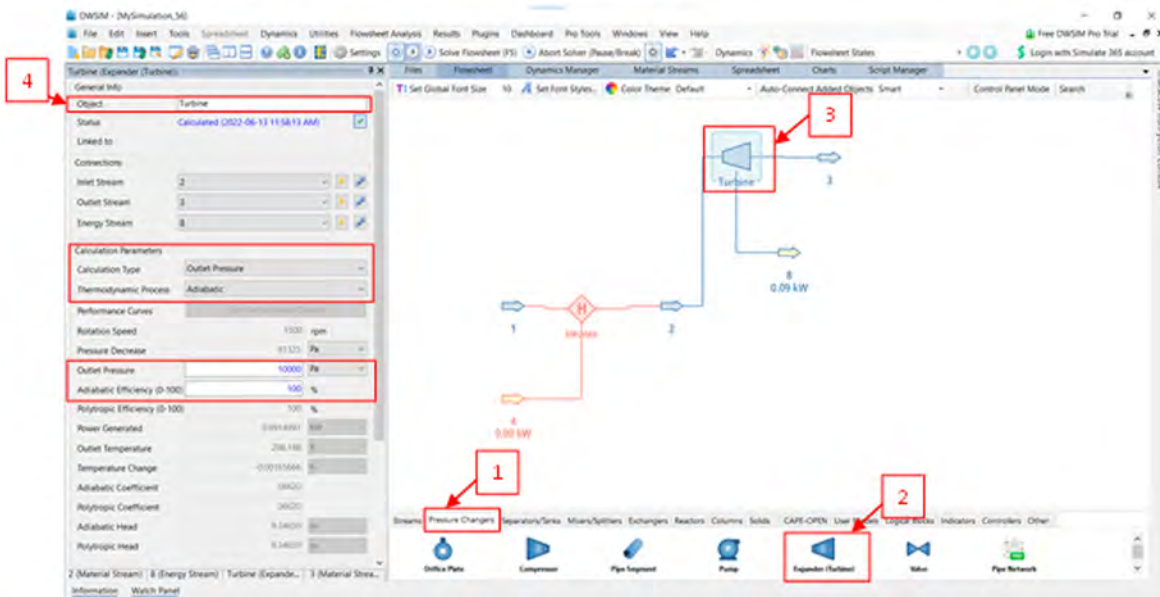
Looking now at the state point after the heater, the turbine inlet, we know both the pressure and temperature of the fluid at this state point from the problem statement. In addition, we are dealing with a steam cycle, so our working fluid is water.

At the outlet of the turbine, we notice that the specific entropy is already known. (It is the same as that for the state point before the turbine because the turbine is isentropic.) We are told in the problem that steam exits at 10 kPa, so we assume the pressure at this state point to have that value. Since we now know both the pressure and the entropy at this state point, we know all of the intensive property values here.

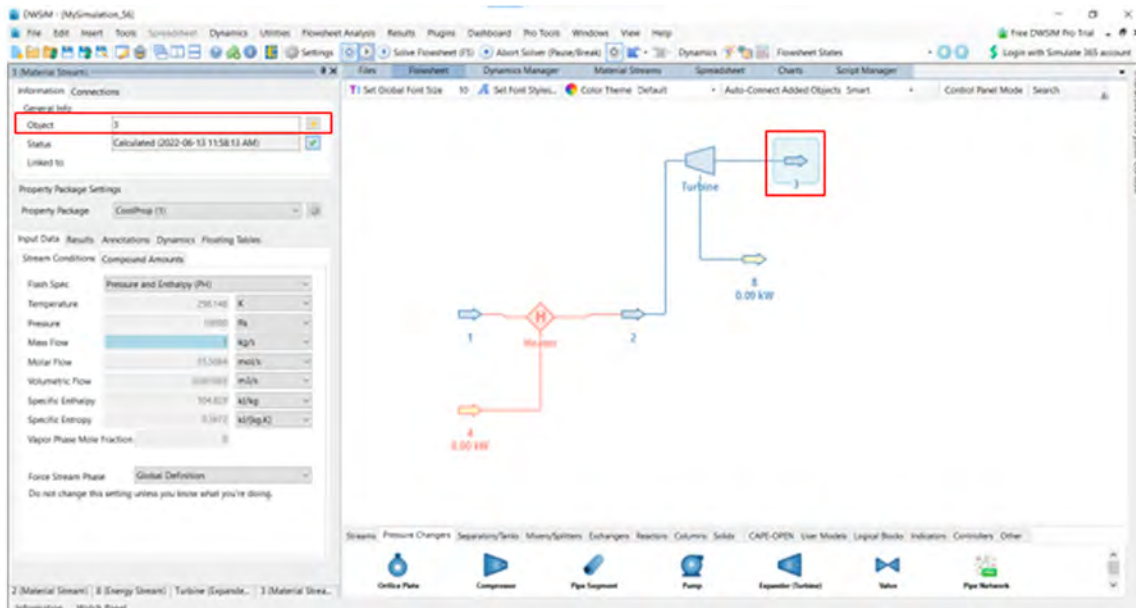
In DWSIM, first select Pressure Changers in the bottom tab of the screen, then select the Expander (Turbine) and drag it to the flowsheet so that it's above the heater. The outlet of the heater should connect automatically to the turbine.

Now, click on your inserted Turbine:

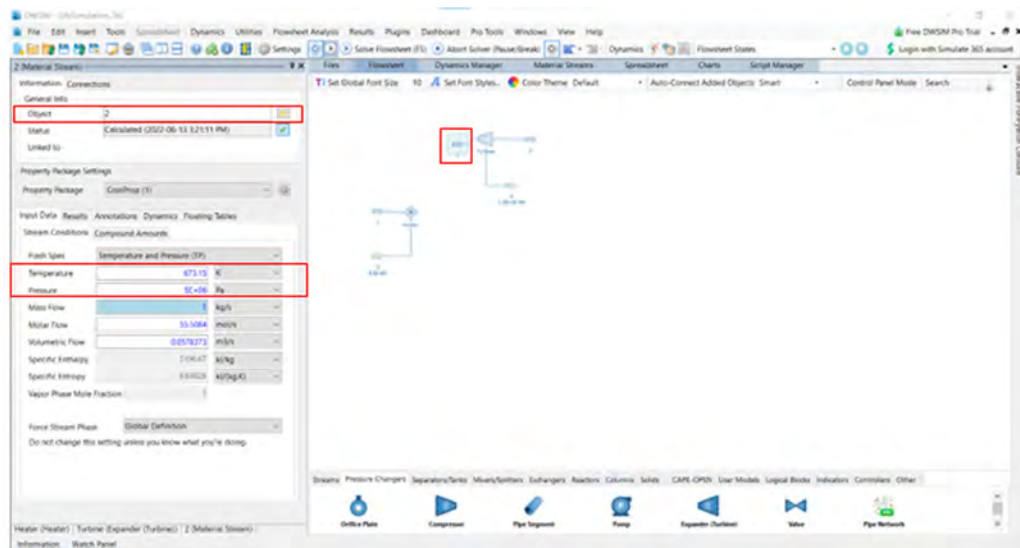
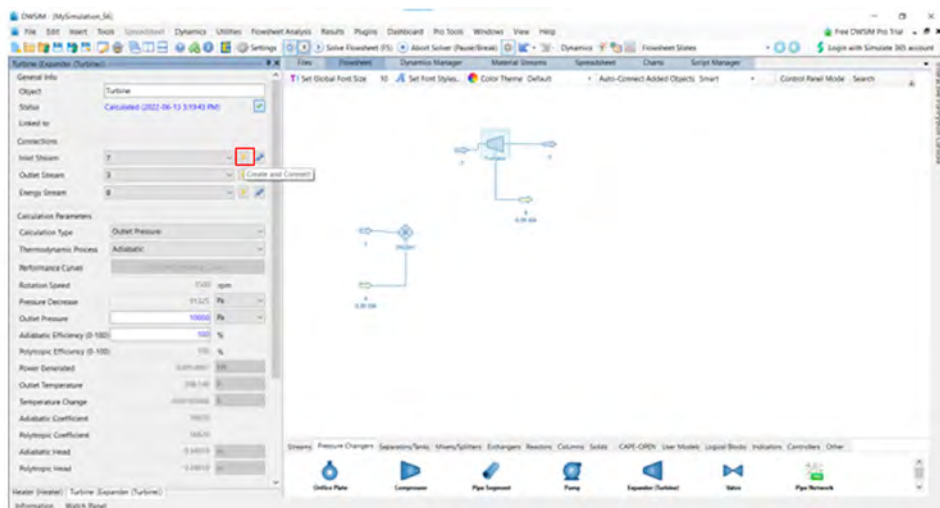
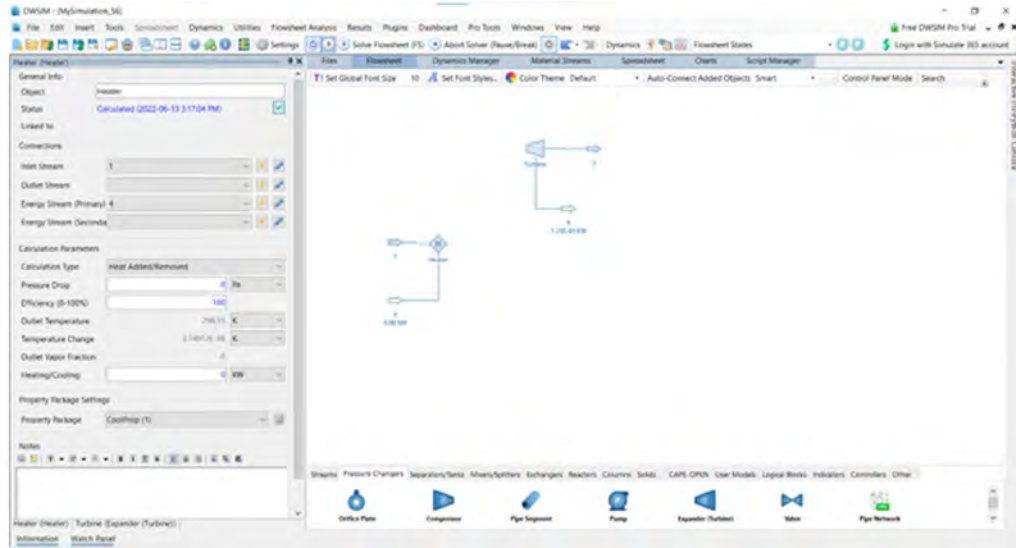
- Change the Object name to “Turbine”.
- Set the Calculation Type to Outlet Pressure and then insert 10 kPa or 10 000 Pa for the Outlet Pressure.
- Set the Thermodynamic Process to Adiabatic. This allows you to change the Adiabatic Efficiency which you can set to 100%. This corresponds to the isentropic efficiency discussed in the lectures.



- Finally, select the outlet arrow and rename it to 3.

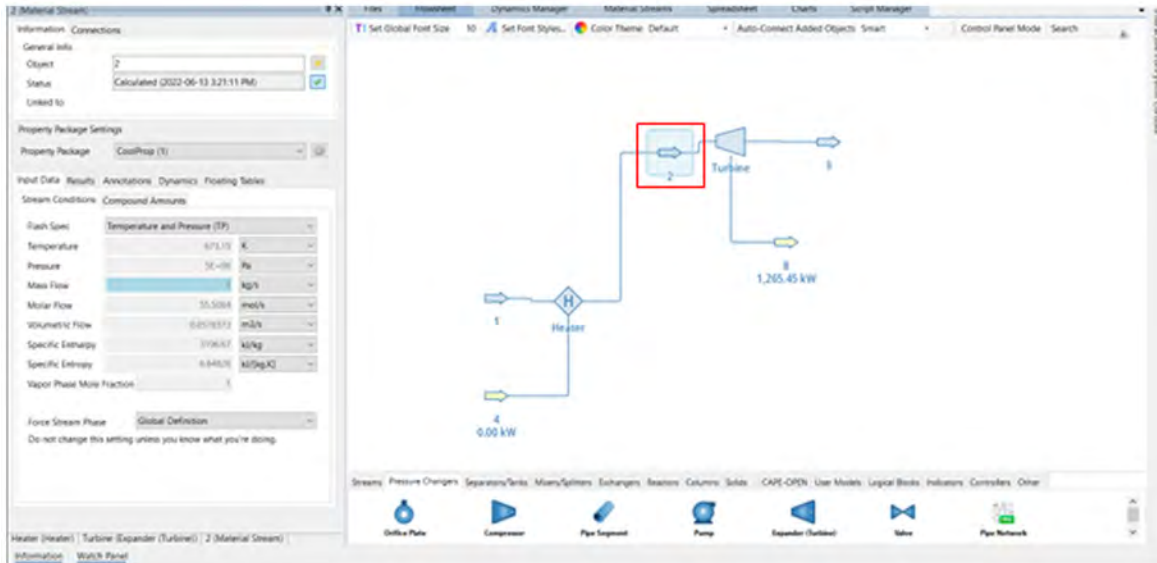


Since we have the inlet values for the turbine, we will delete arrow 2, and then recreate an inlet arrow for the turbine. This new inlet can now have specific values that we know: $T = 400^{\circ}\text{C}$ and $P = 5\text{ MPa}$. These steps are shown in the next 3 screenshots.



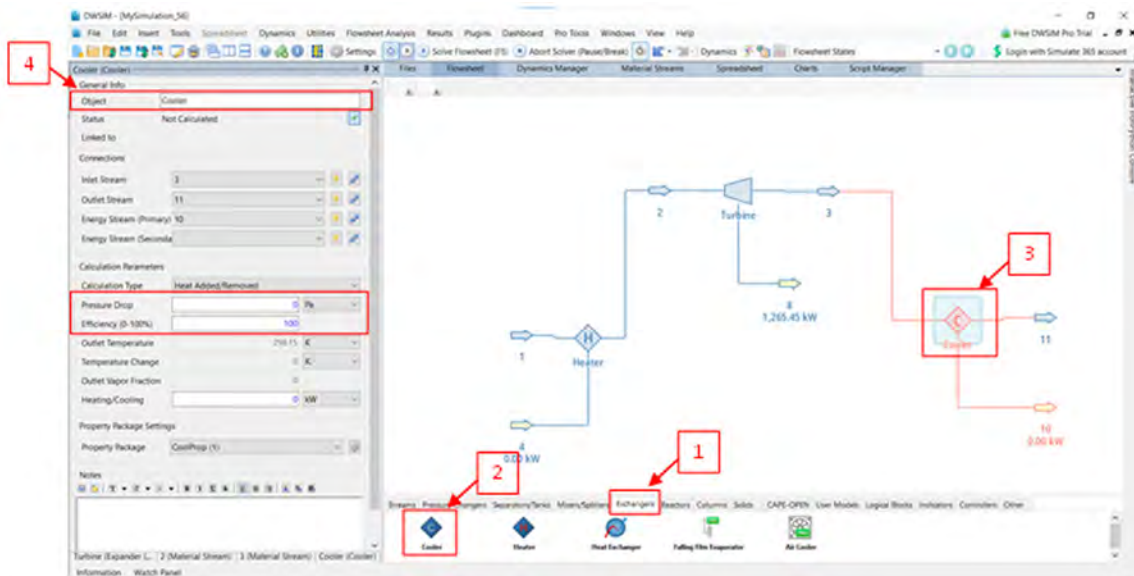
Now select the heater and choose for the Outlet Stream number 2. The heater will connect directly to the turbine.

Now, if you click on arrow 2 you will see that the properties that we inserted are locked in.

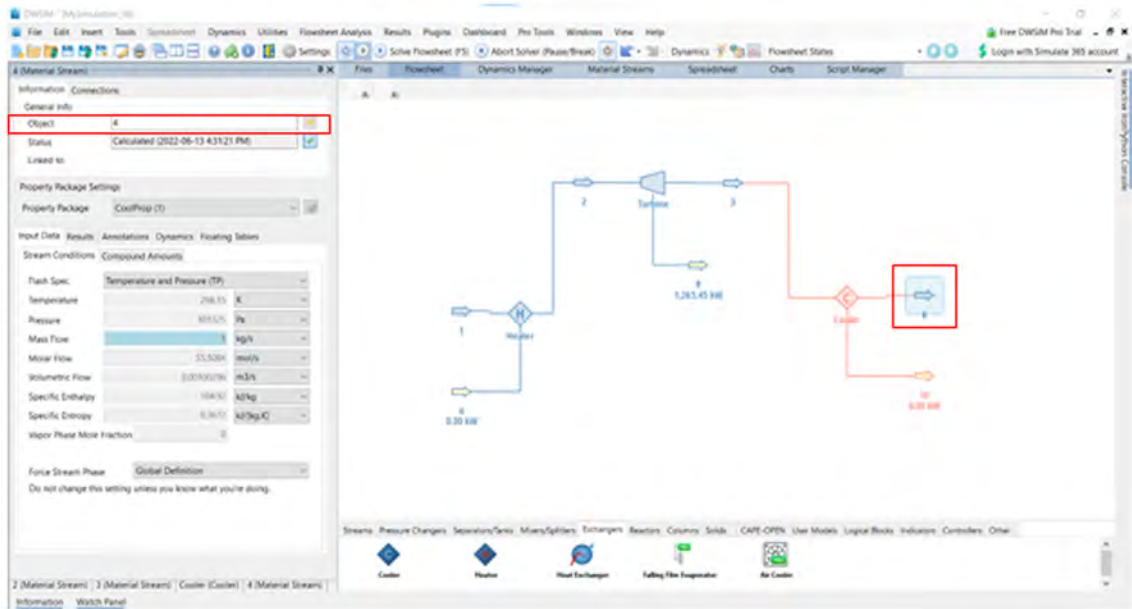


THE COOLER

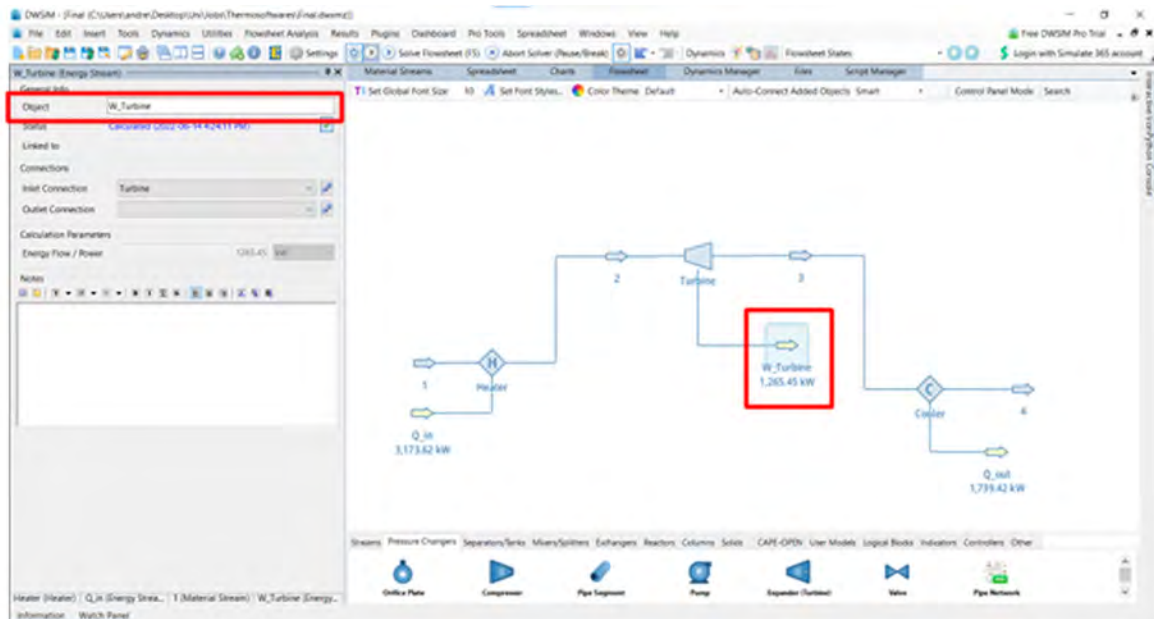
Similar to an ideal heater (and for the same reasons), an ideal cooler has no pressure drop, so we make the isobaric assumption here as we did for the heater. The steps are highlight in the image below.



Now select the outlet arrow of the cooler and change the object name to 4.



Before proceeding to the next step, select the third arrow coming out of each component, in other words the energy stream and rename them as the picture shows below. The picture shows how to do it for the turbine, repeat the same steps for the cooler and the heater.



THE PUMP

We are given no explicit information about the pump, but, as for turbines, ideal pumps are adiabatic and reversible, or isentropic. We make this assumption here.

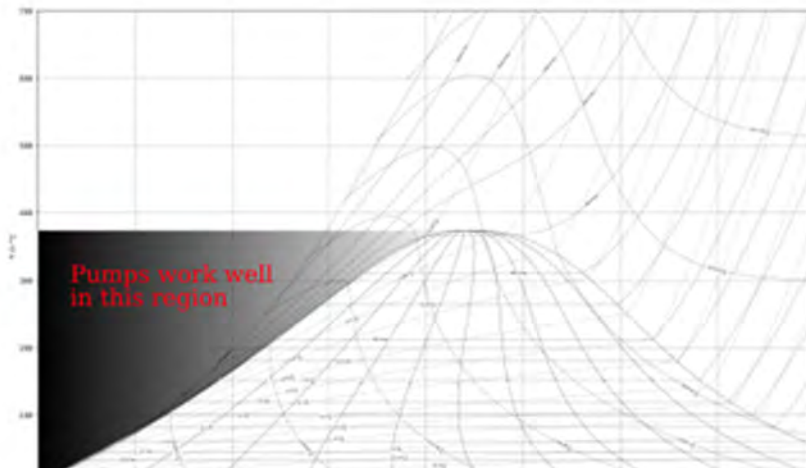


Figure 2.2: T-s diagram for water

The pump inlet is a state point where our own knowledge and reasoning about cycles is key to making assumptions. We know pumps can be damaged by non-liquids. To avoid this, the cooler must condense all of the steam leaving the turbine into a liquid before we send it to the pump. So, we at least want to cool our saturated working fluid to 0% quality before sending it to the pump. Figure 2.2 shows the region to which we must cool the working fluid before safely using a pump.

Of course, pumps can work with compressed liquids as well, so we could cool the fluid even past saturated fluid down into the compressed liquid region. We do not do this for several reasons related to cycle efficiency.

In DWSIM, we can specify the Vapor Fraction at the inlet of the pump. In our case, we'll set the value to 0.

At the pump outlet, the state is already known because we know the pressure (the same as for the turbine inlet for an isobaric heater) and the entropy (the same as for the pump inlet for an isentropic pump). In cases where this state is not known, it is because we have a non-ideal component in our system (such as a non-isobaric heater). In those cases the problem statement will typically include information about the pump outlet pressure or the pump's pressure ratio.

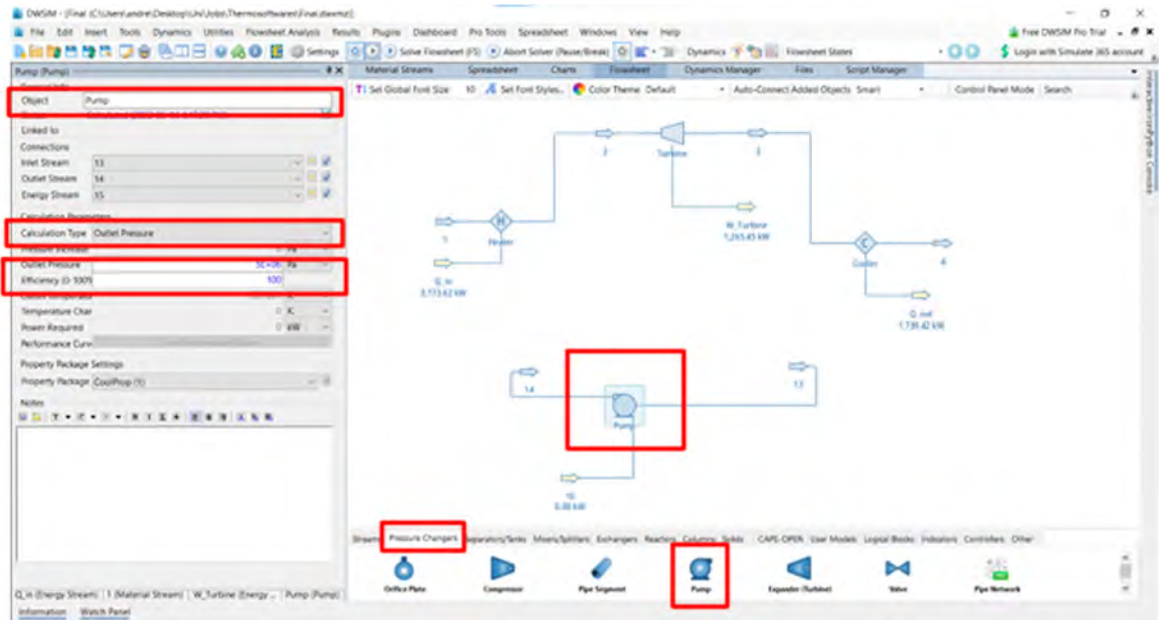
Notes:

Sometimes we can't cool the working fluid just until it is a saturated liquid. Most often this is because our cooling source is at a specified temperature, and we cannot remove the working fluid from the cooler early enough. In these cases, we are usually given a temperature for the exit state of the condenser.

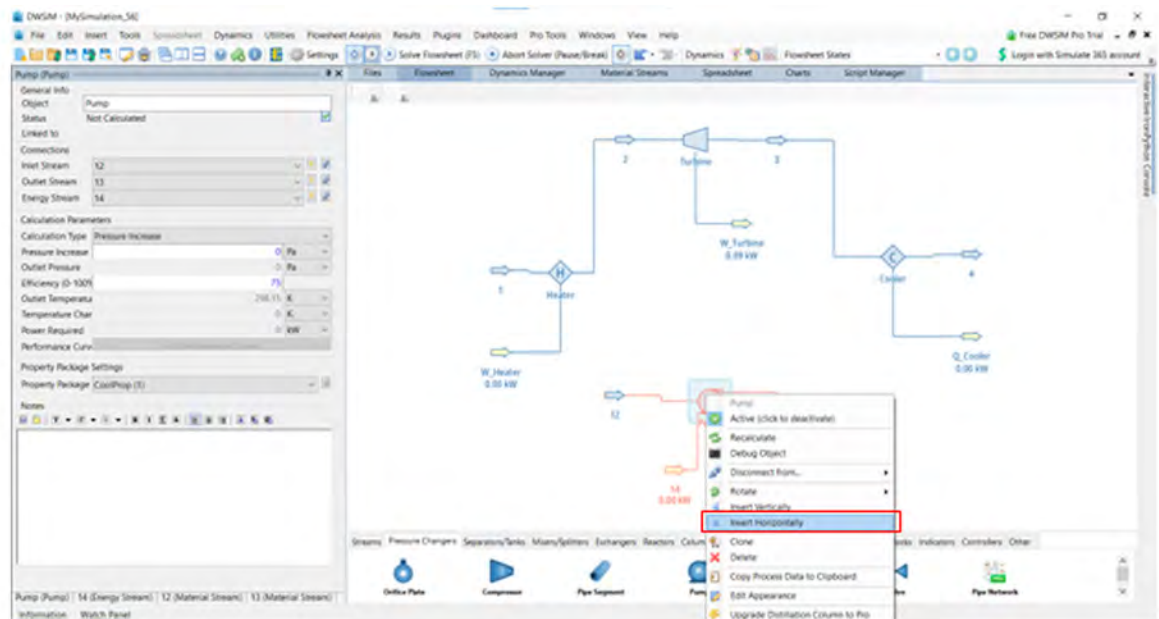
In DWSIM, select Pressure Changers, then select the Pump and drag it to the flowsheet.

Now, click on your inserted Pump:

- Change the Object name to “Pump”.
- Set the efficiency to 100%.
- Set Calculation Type to Outlet Pressure and set the Outlet Pressure to 5MPa.

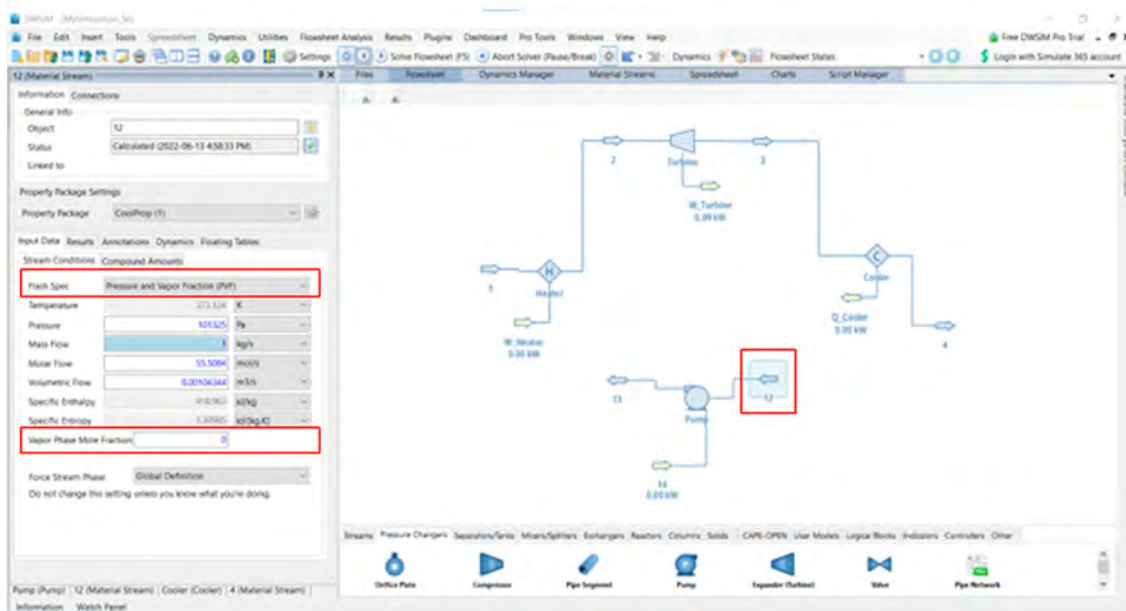


Select the pump and then right click and choose the option to invert horizontally.

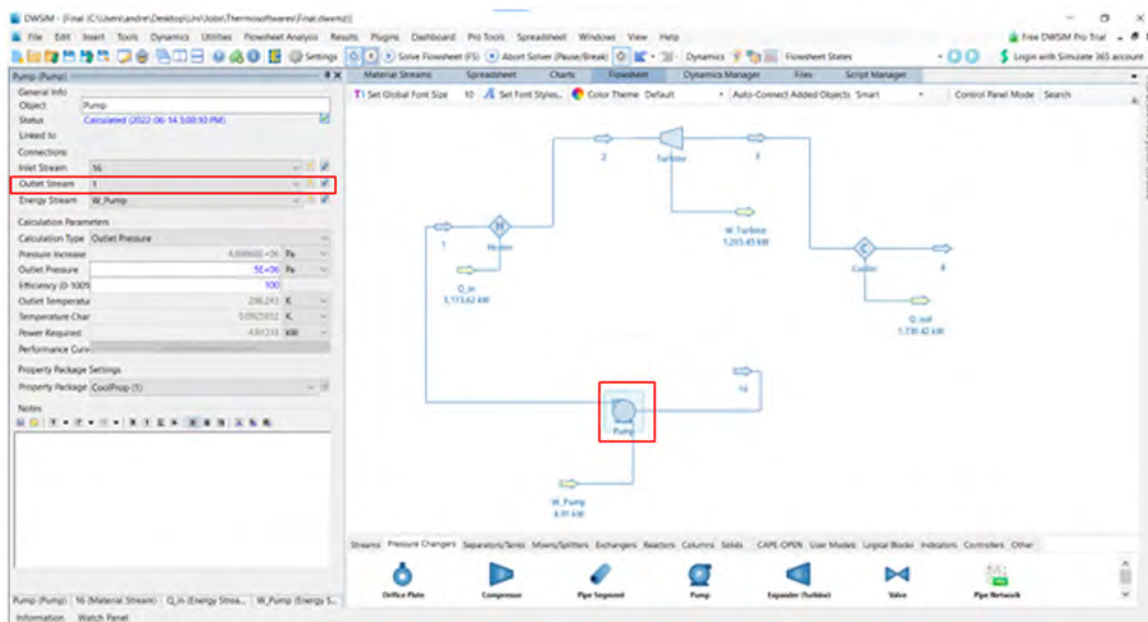


The pump is now facing the right way. Rearrange your arrows so that it would look like the first image with the pump.

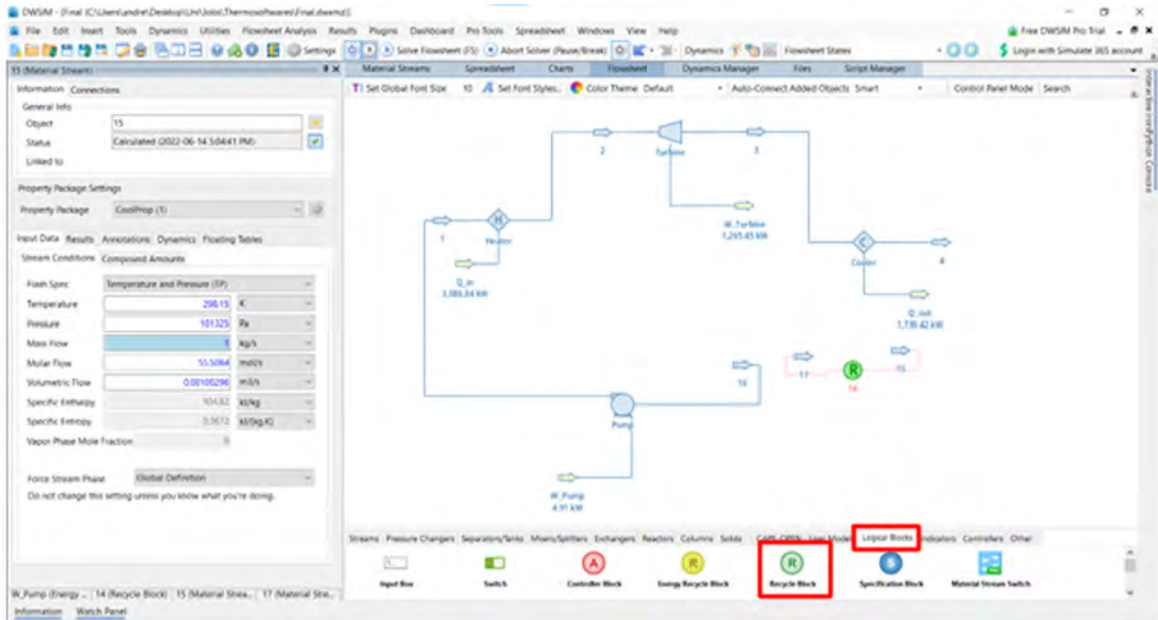
Select the inlet of the pump and set the Flash Spec to Pressure and Vapor Fraction (PVF) and then set the Vapor Phase Mole Fraction to 0. This setting is how we assume, in the software, that $x=0$, as discussed in the lectures.



Now select the pump again and choose the outlet stream to be I. The pump should now be connected to the heater. Don't forget to rename your energy stream as shown below.

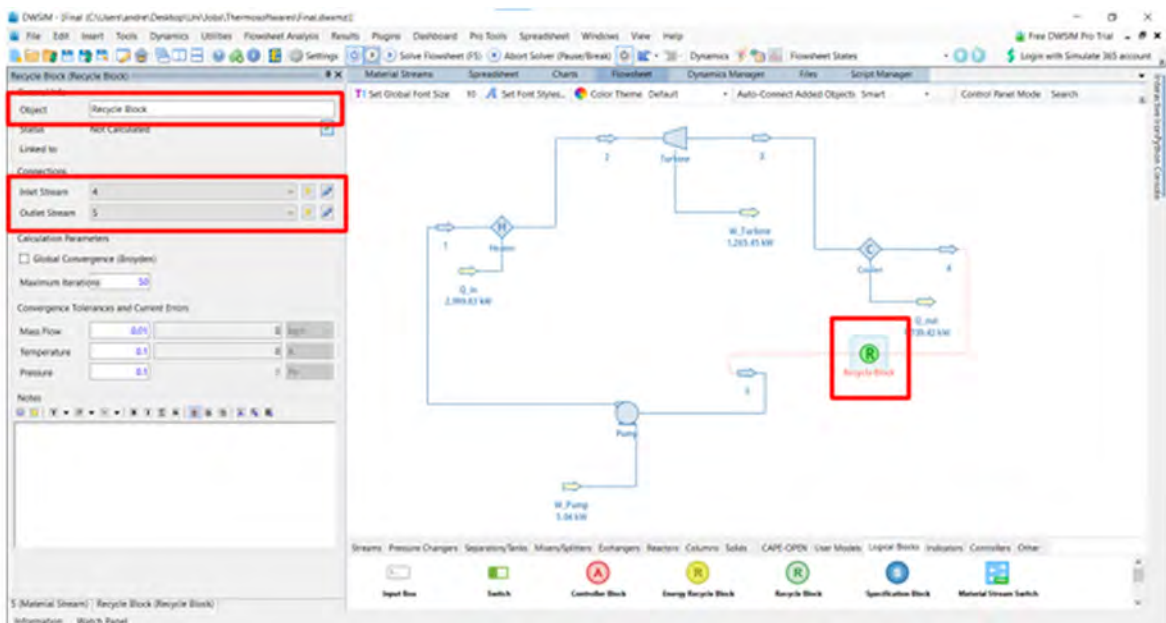


Now to create a closed cycle, select Logical Blocks and then drag the Recycle Block to the Flow sheet. Right click and invert it horizontally and rearrange your arrows so that your model looks like the image below.

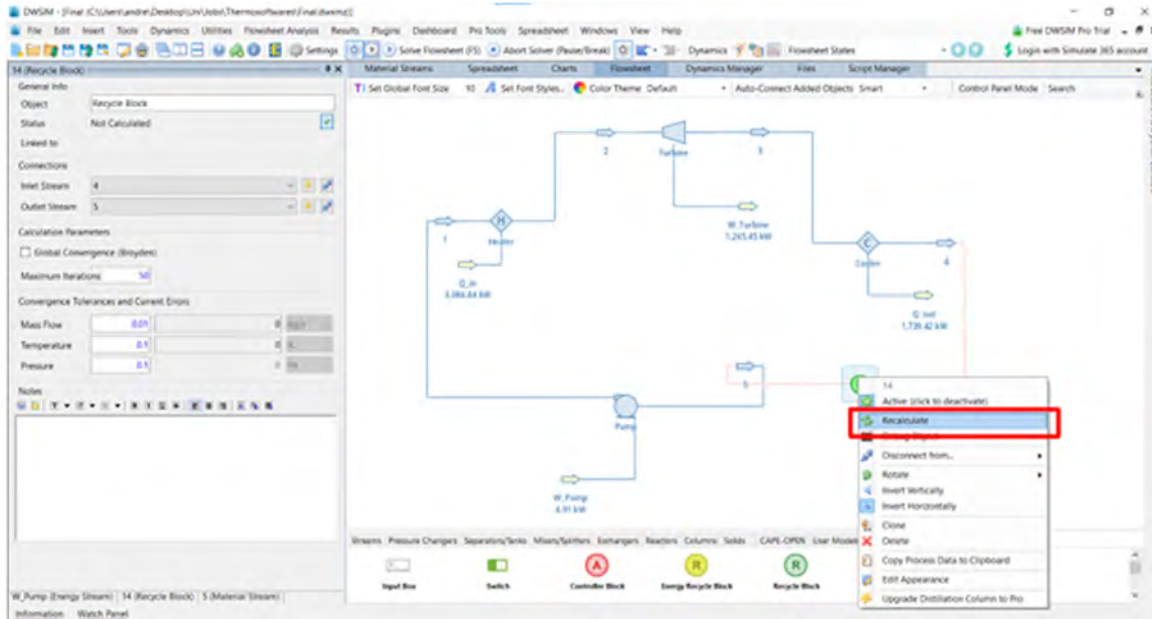


Select the Recycle Block:

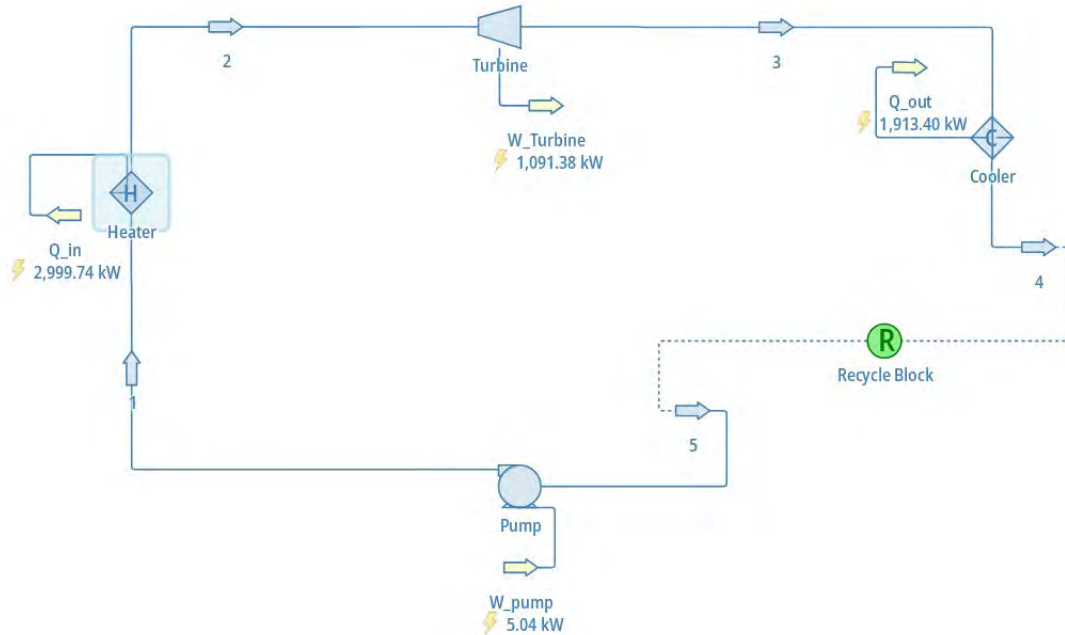
- Rename the object to Recycle Block.
- Choose the inlet stream to be 4 and the outlet stream to be 16.
- Select the arrow 16 and rename it to 5 as we have done previously. You should obtain the model below.



Now right click on the Recycle Block and select Recalculate.



You can rearrange your arrows and components by right clicking on each one of them and rotating them in an ideal arrangement. The image below shows the completed cycle.



FINISHING THE PROBLEM

DWSIM doesn't have the tools to calculate the efficiency of the cycle. However, once the work and heat values are found, it is very simple to calculate the efficiency of the cycle. DWSIM helped us skip over the tedious steps of going through the tables and finding the intensive values at each state point while avoiding common mistakes made while reading and noting the values.

To find the thermal efficiency, you can use the following equation:

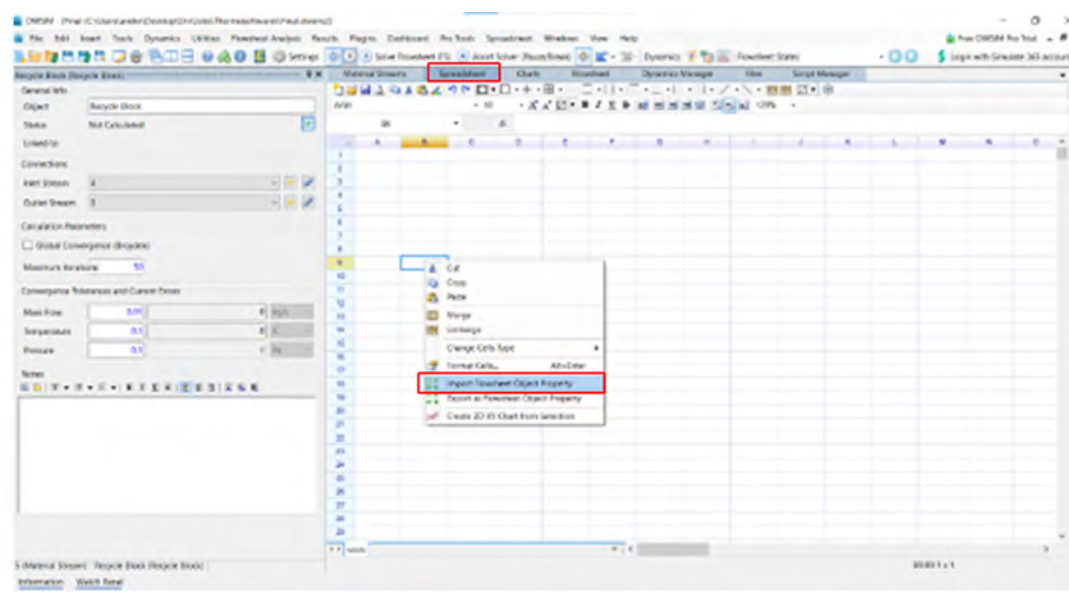
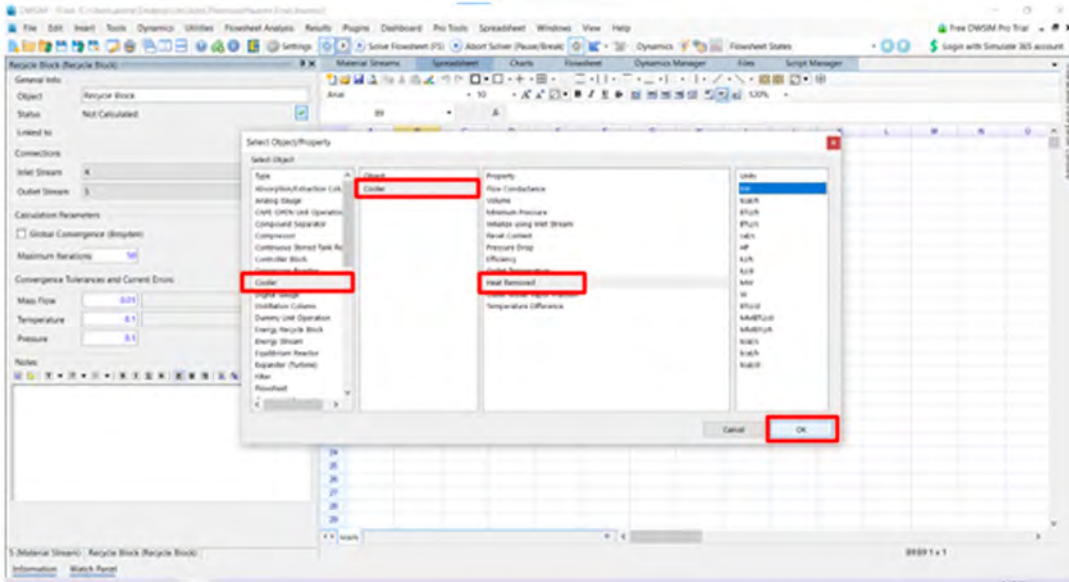
$$\eta_{thermal} = \frac{W_{net}}{Q} = \frac{W_{Turbine} - W_{pump}}{Q} = 36.21\%$$

To find the Carnot efficiency, you can use the following equation:

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} = 52.6\%$$

You can use the spreadsheet tab available on DWSIM or you can make your own spreadsheet separately. If you do use the spreadsheet in DWSIM, you have the option to import the value directly to the cell selected. The images below show how that can be done.

	A	B	C	D	E	F	G	H	I	J	K
1											
2											
3	W_Turbine	1091.37862835188	kW								
4	W_Pump	5.04125303138582	kW								
5	W_net	1086.33737532049	kW								
6	Q_in	2999.73812195342	kW								
7	Q_out	1913.40074663295	kW								
8	n_th	36.21	%								
9	T_H	673.15	K								
10	T_C	318.957548207023	K								
11	n_C	52.62	%								
12											
13											
14											



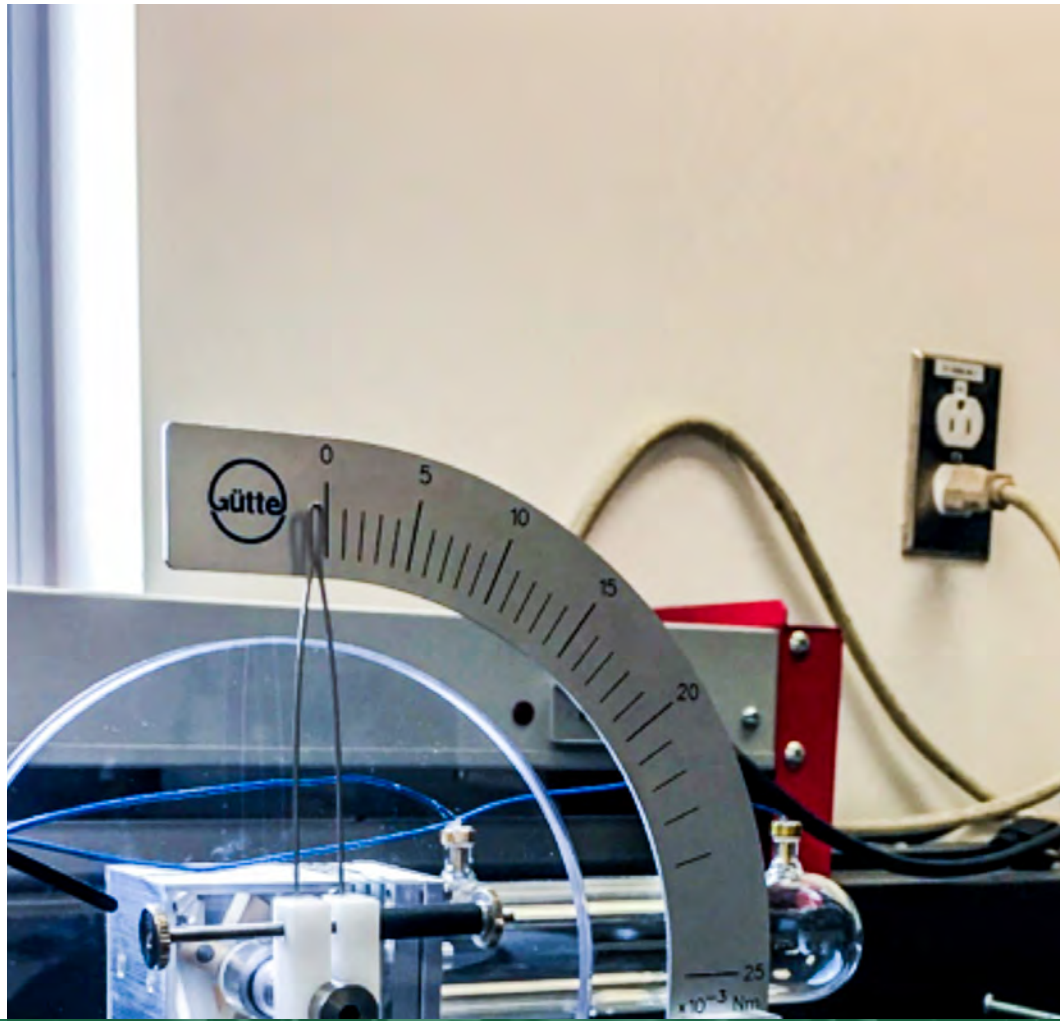
ASSIGNMENT

Note: This is NOT a formal report. Simply answer the problems as an assignment. Make sure to include a title page.

1. Consider an ideal Rankine cycle in which steam enters the turbine at pressure of 3 MPa and a temperature of 450°C. The pressure within the condenser is 50 kPa.
 - a. Compute the actual Carnot and thermal efficiencies.
 - b. Plot the T-s diagram for the actual Rankine cycle.
 - c. Plot the variations in (i) Carnot efficiency, (ii) thermal efficiency and (iii) steam quality at turbine outlet; for inlet turbine temperatures of [450 500 550 600] °C. Tabulate and discuss the results.
 - d. Plot the variations in (i) Carnot efficiency, (ii) thermal efficiency and (iii) steam quality at turbine outlet; for condenser pressures of [50 40 30 20 10] kPa. Tabulate and discuss the results.
 - e. Plot the variations in (i) Carnot efficiency, (ii) thermal efficiency and (iii) back work ratio; for condenser exit temperatures of [80 70 60 50 20] °C. Tabulate and discuss the results.
 - f. Plot the variations in (i) Carnot efficiency, (ii) thermal efficiency and (iii) steam quality at turbine outlet; for turbine pressures of [2 5 10 15 20] MPa. Tabulate and discuss the results.
2. Consider now an ideal regeneration Rankine cycle working under the same conditions as above.
 - a. Represent using DWSIM the ideal regenerative Rankine cycle.
 - b. Plot the variations in thermal efficiency for feed water pressures of [200 400 600 800 1000] kPa. Tabulate and discuss the results..
3. Consider a steam power plant with a 3-stage turbine. The steam is reheated between stages 1 and 2, and steam is extracted between stages 2 and 3 and sent to an open feedwater heater. All components, except the open feedwater heater, are ideal. The open feedwater heater is isobaric. The following components operate at the following pressures or temperatures:
 - i. Feedwater Heater: 0.5 MPa
 - ii. Main Boiler: 5 MPa
 - iii. Reheater Boiler: 0.9 MPa
 - iv. Condenser: 50 kPa

There is 5 degrees of overcooling at the exit of the condenser. The exit temperature of both the main and reheater boilers is 450°C.

- a. Sketch the cycle diagram components and the way they are connected using DWSIM.
- b. To successfully close this system and calculate all of its properties, you must be provided with one more piece of information. There are two logical choices, in other words, two items of technical data could be provided which could be easily measured in a real life situation. What are those two pieces of information? Explain your answer.
- c. From your knowledge of how pumps and turbines work, give the possible, physical ranges of the two parameters from b.
- d. Pick one of the two parameters from b and plot the thermal efficiency of the system against the value of the parameter over the entire range determined in c.



LAB

3

STIRLING ENGINE



INTRODUCTION

When air is heated it expands, and when it is cooled it contracts. Stirling engines work by cyclically heating and cooling air inside a leak tight container and using the pressure changes to drive a piston. The heating and cooling process works like this: One part of the engine is kept hot while another part is kept cold. A mechanism then moves the air back and forth between the hot side and the cold side. When the air is moved to the hot side, it expands and pushes up on the piston, and when the air is moved back to the cold side, it contracts and pulls down on the piston.

OPERATION

While Stirling engines are conceptually quite simple, understanding how any particular engine design works is often quite difficult because there are hundreds of different mechanical configurations that can achieve the Stirling cycle. A typical Stirling engine is a displacement-type engine that uses two separate pistons, connected to a common flywheel (see Figure 3.1). One piston is the working or working piston; it fits snugly into the cylinder and maintains the seals on the working air. The other, a displacement piston, is moving freely inside its cylinder, shifting the working air through the gap between the piston and the cylinder from the hot to the cold end of the cylinder and back again

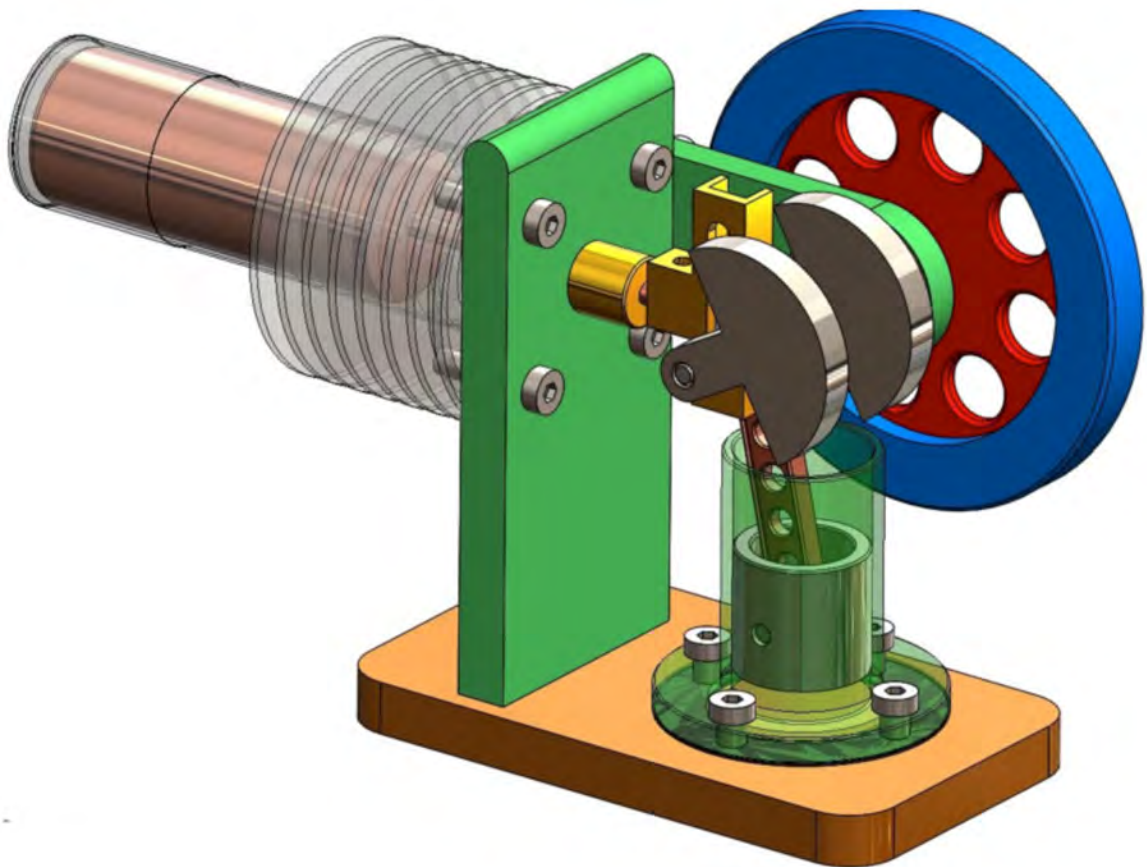


Figure 3.1: Typical Stirling Engine modeled in Solidworks

The ideal Stirling cycle can be divided into four parts (see Figure 3.2):

- I. **Expansion** - Gas is shifted to the hot end by the displacement piston; it expands as it heats up, and pushes the working piston which in turn rotates the flywheel;
- II. **Cooling** - Displacement piston moves, shifting the gas toward the cold end; heat is lost from the gas;
- III. **Compression** - Cooled gas is re-compressed by the inertia of the flywheel pushing the working piston.
- IV. **Heating** - Gas is compressed by the working piston, the displacement piston shifts it to the hot end, where the heat is absorbed into the gas.

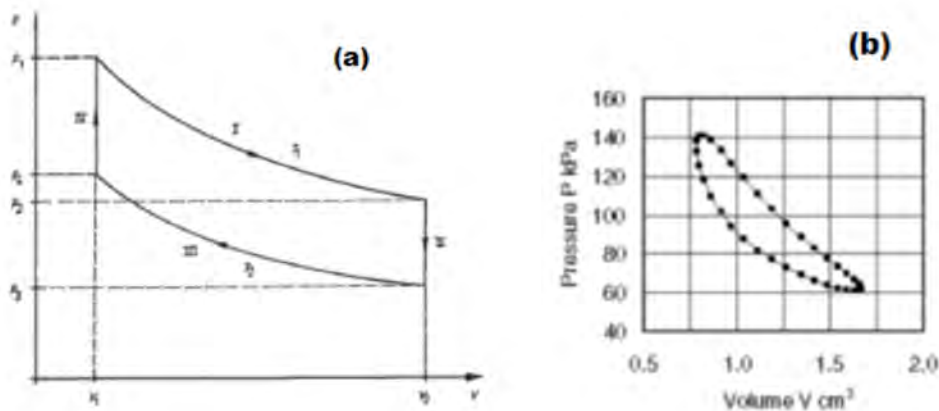


Figure 3.2: PV diagram of the Stirling cycle (a) Ideal (b) Real

As we follow along the curve made by the measured pairs of pressure and volume, the area on the PV diagram inside the cyclical trajectory of the working cycle of the engine represents the amount of mechanical work performed by it. The work is being done by the gas on the flywheel along the upper curve and by the flywheel on the gas along the lower curve; the difference is the net work done by the engine.

Four snapshots from I to IV show the relative positions of the displacement and working pistons illustrated schematically in Figure 3.3. Figure 3.4 shows a more realistic plot of the positions of the two pistons during continuous rotation of the flywheel. Both pistons are attached to the same flywheel but at 90° to each other. As a consequence, the solid and dashed lines are a quarter of a cycle out of phase with each other. The grey region in Part II shows the part of the cycle where the working piston is near its lowest point and the gas volume is approximately at its maximum. The area above the dashed line represents the fraction of the total volume that is above the displacement piston, in thermal contact with the hot end of the cylinder. Since it takes less work to compress the gas when it is cold (against lower gas pressure) than the work done by the gas on the piston when it is hot (gas exerting higher pressure over the same piston travel distance), there is a net conversion of heat into mechanical work.

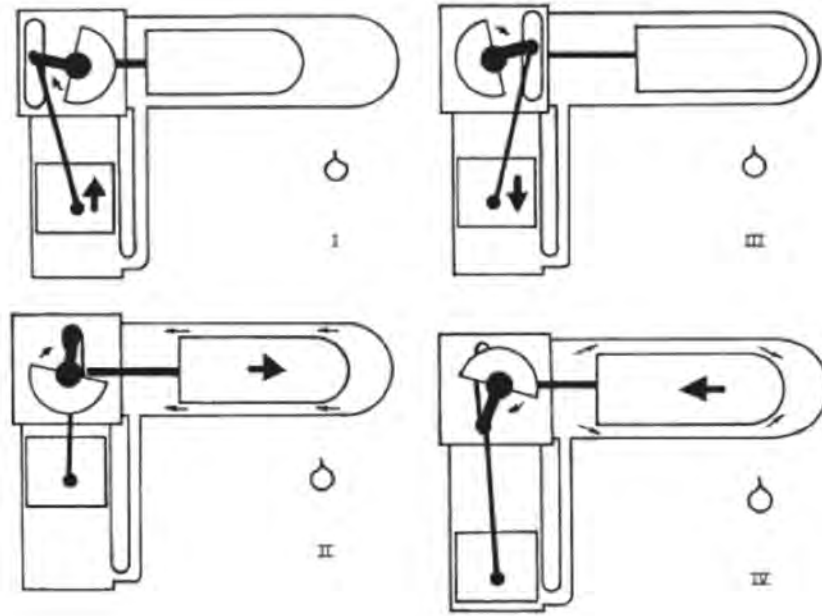


Figure 3.3: Relative position of the displacement and working pistons for one cycle

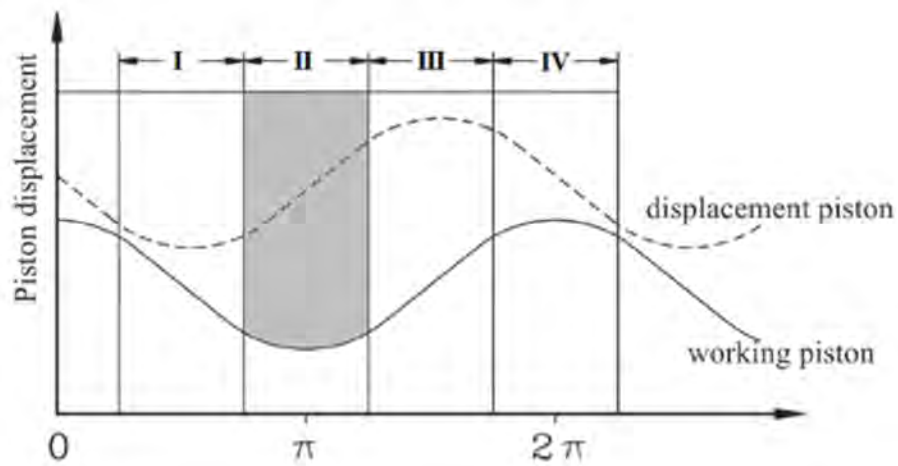


Figure 3.4: Realistic representation of the Stirling cycle.

EQUIPMENT

The Stirling engine can be used for qualitative and quantitative investigations of the Stirling cycle. It can be operated in two different modes:

- 1) Heat Engine
- 2) Heat Pump

Typically, the Stirling engine is used as a heat engine; heat is applied to the round end of the glass tube containing the displacer piston and the engine uses some of this heat energy to perform mechanical work. If the engine is connected to a motor/generator unit, some of this mechanical energy is converted to electric energy. As a heat engine, the Stirling engine will always turn in the same direction.

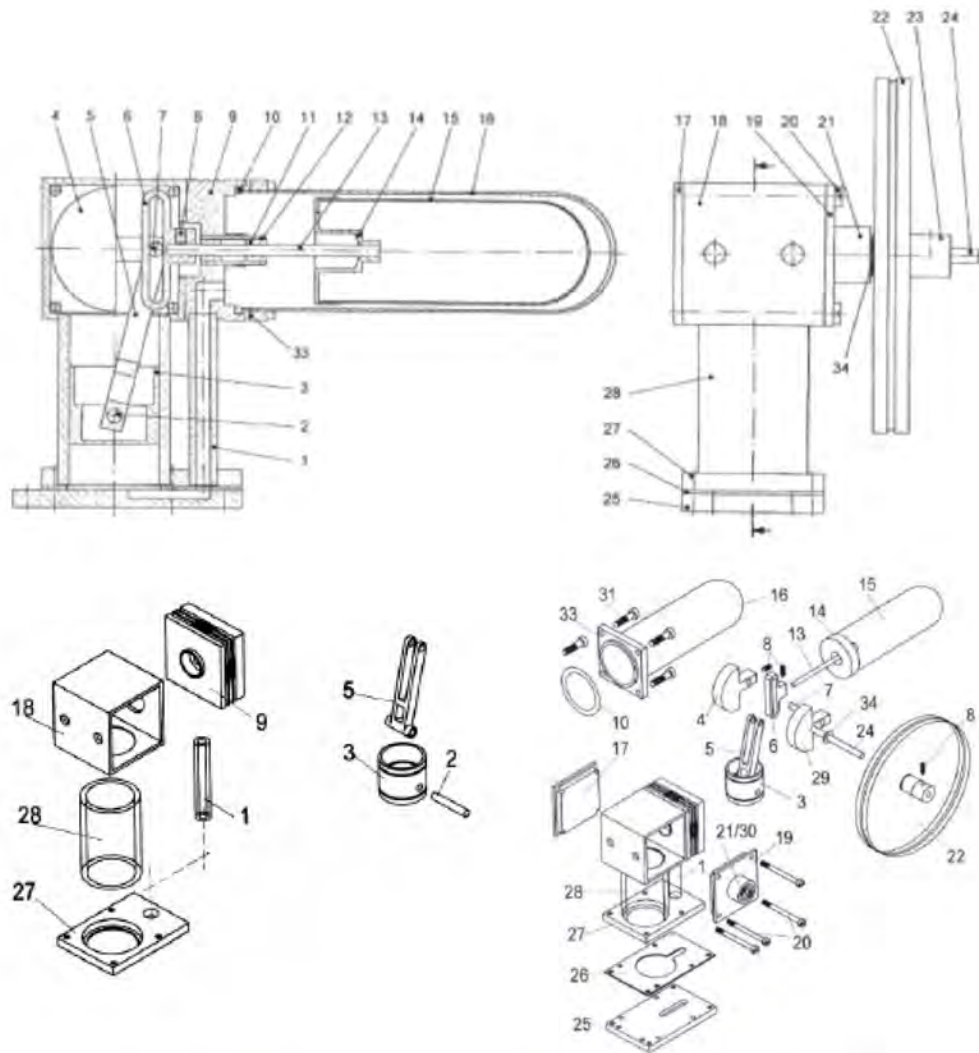
If one uses an external motor to drive the Stirling engine through its thermal cycle, the net effect is the reverse conversion from mechanical energy into thermal one, heating up one end and cooling down the other end of the cylinder. If the Stirling engine is used as a heat pump, the opposite of a heat engine, a DC voltage is applied to the motor that rotates the flywheel and moves the pistons. The electrical energy is expended to transfer heat and thus create a temperature difference between the two ends of the cylinder. The direction of the transfer of heat depends on the direction of rotation. Thus the engine can heat as well as cool the round end of the glass tube relative to the other end that has a large metal heat reservoir attached to it exchanging heat with the surrounding air.

STIRLING ENGINE

The displacement cylinder and piston are made of heat resistant glass. It is also equipped with two recessed temperature measurement sockets to accept sheathed thermocouples to measure the temperature of the hot and cold. The working cylinder, flywheel and gearbox cover are made of acrylic glass. This allows for very clear observation of the individual sequences of motion at all times. The flywheel has markings to allow measurement of the RPMs using a light barrier. The crankshafts are equipped with ball bearings and made of hardened steel. The connecting rods consist of wear-resistant plastic.

TECHNICAL DATA

- No Load Speed: 1000 RPM (minimum)
- Maximum Power: 3.5 W
- Resolution: 3.5×10^{-3} N-m
- Flywheel Diameter: 140 mm (Base Plate); 70 mm (Solar)
- Working Piston Diameter: 25 mm
- Displacer Diameter: 30 mm
- Maximum Volume: 44 cm^3
- Minimum Volume: 32 cm^3
- Minimum Temperature Difference: 100°C



1 Connecting tube	19 Plate with bushing
2 Cylindrical pin	20 Cheese-head screw M3x45 (4x)
3 Power piston	21 Bush
4 Crank cheek	22 Flywheel
5 Connecting rod	23 Flywheel bush
6 Crank	24 Crankshaft
7 Crank pin	25 Base plate
8 Headless screw M3x4 (2x)	26 Gasket
9 Radiator box	27 Power piston flange
10 O-ring	28 Power cylinder
11 Bush (2x)	29 Crank disk
12 Displacer bush	30 Ball bearing (2x)
13 Displacer rod	31 Cheese head screw M3x10 (4x)
14 Displacer bottom plate	32 Flat head screw M3x10 (4x)
15 Displacer piston	33 Displacer cylinder flange
16 Displacer cylinder	34 Shim
17 Side plate	35 Oil for displacer rod
18 Crankcase	36 Oil for power piston

HEAT SOURCES

A Stirling engine is a heat engine that is vastly different from the internal combustion engine in a car or a steam engine. It uses air as working fluid and is powered by an external heat source. Thus the engine has the potential to use any heat source as a fuel like biomass, waste heat or solar energy. As the limitation of our fossil energy resources became obvious, scientists and engineers recalled the old Stirling principle to use alternative energy sources. In this experiment a base plate with an alcohol burner as the heat source to drive a Stirling engine:

BASE PLATE CONFIGURATION

The Stirling engine is placed on an acrylic base plate and firmly screwed from the bottom with two knurled screws as shown in Figure 3.5. Two other knurled screws on top of the base plate are used to attach the GT03 motor/generator unit or the torque meter scale. The heat source is an alcohol (or methyl hydrate) burner with a heating value = 25 kJ/g.

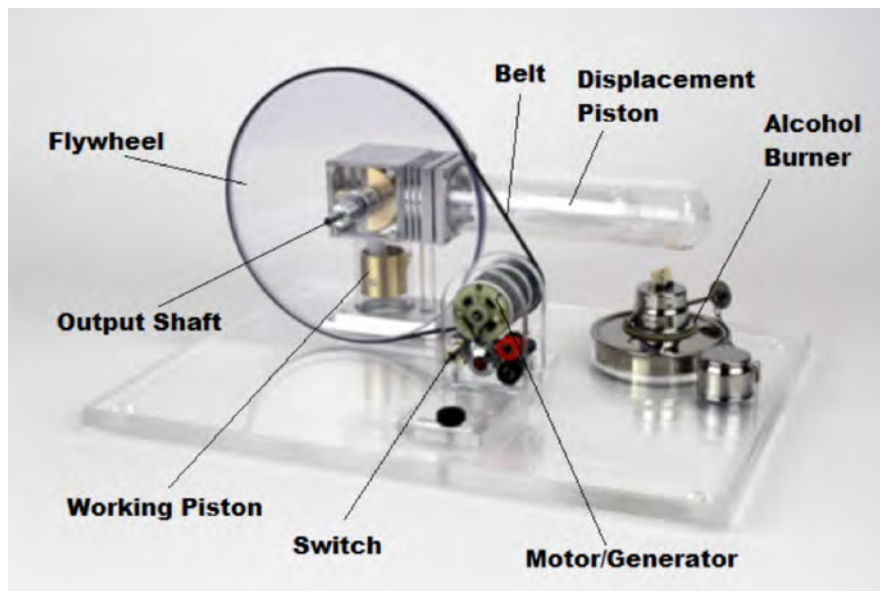


Figure 3.5: Base Plate Stirling Engine

The flywheel normally remains fastened with the aid of an Allen key. After the flywheel has been remounted, the shaft should be pulled slightly outwards and only a small air gap (i.e. the thickness of a sheet of paper) should be present between the flywheel and the motor housing so that the shaft does not have too much play when in operation.

GT03 MOTOR/GENERATOR UNIT

The GT03 motor/generator unit has two pulleys of different size with which the influence of the transmission ratio on the power and speed of the Stirling engine can be demonstrated. A belt links the flywheel to the motor. The operating mode is selected by a switch to either generator or motor mode. In generator mode the integrated lamp lights. Two output sockets are wired in parallel to the lamp socket, enabling a variable resistance to be connected. For operation as a motor, a DC voltage from a power supply is applied to the input sockets. Maximum voltage is 12 Volts DC.

TORQUE METER

The inner metal part of the pointer (Prony brake with inclination weight) is fastened to the shaft of the Stirling motor in front of the flywheel using the Allen key. The friction between the metal part and the pointer can be changed with the adjustment screw on the pointer. When the Stirling motor runs, the pointer is carefully pushed onto the shaft. The friction should then be slowly increased; it should not be so high that motor comes to rest. The set torque is indicated on the scale. See Figure 3.6.



Figure 3.6: Torque Meter

The measurement range of the torque meter is 25×10^{-3} N-m with a resolution of 1×10^{-3} N-m. The balancing weight is 50 g.

THEORY

According to first law of thermodynamics, when thermal energy is supplied to an isolated system, its amount is equal to the sum of the internal energy increase of the system and the mechanical work supplied by the latter:

$$dQ = dU + PdV \quad (3.1)$$

It is important for the Stirling engine that the thermal energy produced during the cooling phase be stored until it can be used again during the heating phase (regeneration principle). Thus during the heating phase, the amount of thermal energy released is absorbed during cooling. In other words, only an exchange of thermal energy takes place within the engine. Mechanical work is merely supplied during expansion and compression. The internal energy remains unchanged during an isothermal process thus work performed during is equal to the absorbed energy (expansion) and released energy (compression).

For an ideal gas:

$$P \cdot V = n \cdot R \cdot T \quad (3.2)$$

where P is the pressure, V is the volume, T is the temperature and n is the number of moles contained in the system. R is the universal gas constant.

The amount of work produced during expansion is:

$$W_1 = -n \cdot R \cdot T_1 \cdot \ln\left(\frac{V_2}{V_1}\right) \quad (3.3)$$

It is negative because this amount of work is supplied.

Consequently, the amount of work exerted during compression is:

$$W_3 = +n \cdot R \cdot T_2 \cdot \ln\left(\frac{V_2}{V_1}\right) \quad (3.4)$$

$|W_1| > W_3$ because $T_1 > T_2$.

The total work W_T is equal to the area of the PV diagram or the sum of W_1 and W_3 or:

$$W_T = -n \cdot R \cdot (T_1 - T_2) \cdot \ln\left(\frac{V_2}{V_1}\right) \quad (3.5)$$

where $R = 8.31 \text{ J/mol-K}$ (the general gas constant).

Only part of the total work can be used as effective mechanical work W_m through exterior loads applied to the engine. The rest contains losses within the Stirling engine such as friction.

Effective mechanical energy during a cycle is calculated using the torque M displayed by the torque meter:

$$W_m = 2 \cdot \pi \cdot M \quad (3.6)$$

The rotational speed of the flywheel is converted to frequency (f) which allows the calculation of the mechanical power P_m :

$$P_m = W_m \cdot f \quad (3.7)$$

Effective electrical power (P_e) is calculated by measuring the voltage (U) and current (I) at the load resistor:

$$P_e = U \cdot I \quad (3.8)$$

The maximum thermal efficiency of a reversible process within a heat engine is equal to the ratio between net work and the amount of supplied heat $Q_1 = -W_1$ or

$$\eta_{th} = \frac{T_1 - T_2}{T_1} \quad (3.9)$$

Carnot found this to be the maximum thermal efficiency for any heat engine which can only be reached theoretically. The efficiency increases with increasing temperature differences.

REFERENCES

1. Instruction Manual, Stirling Motor GT03 and Solar Set Indoor, Stirling Shop, Germany.
2. C.G. Deacon, R. Goulding, C. Hardiass, B. deYoung, Demonstration Experiments with a Stirling Engine, Phys. Educ., vol. 29, 1994, pp 180-183.
3. www.3bscientific.de/product-manual/1002594_EN.pdf (Accessed July 2017).
4. www.leybold-shop.com/physics/physics-equipment/heat/heat-and-work/thermal-machines/hot-air-engine-p-388176.html (Accessed July 2017).
5. youtu.be/tNtEZ_UNtwg (Accessed July 2017).

EXERCISE A: MEASURING MECHANICAL POWER (SETUP #1)

PROCEDURE

1. Weigh initial weight of the alcohol burner using the provided digital scale.
2. Light the burner and start the timer.
3. After a minute, turn the flywheel to start the Stirling engine.
4. When thermal equilibrium is reached (approximately 5 minutes), record the two temperatures from the temperature display unit and rotational speed using the tachometer pointed on the flywheel mark. All data is recorded on the data sheet found at the end of this lab manual.
5. Fix the pointer on the flywheel axis.
6. Apply a torque of about 2.5×10^{-3} N-m using the torque meter by adjusting the screw on the pointer carefully for it not to oscillate.
7. Record the temperatures and rotational speed.
8. Repeat for increasing torque at intervals of approximately 2.5×10^{-3} N-m up to 15×10^{-3} N-m or when the engine stops.
9. Turn off the alcohol burner by placing the cover over the open flame.
10. Record the time elapsed and the final weight of the alcohol burner.

RESULTS /DISCUSSION

1. Assume a value of $n = 3.1 \times 10^{-3}$ moles, calculate the following for each torque setting:
 - Total Work in [mJ]
 - Rotational Frequency in [Hz]
 - Mechanical Work in [mJ]
 - Mechanical Power in [mW]
 - Frictional Work in [mJ]

Show sample calculations and tabulate all your results.

2. Plot a graph of the total work, mechanical work and friction work versus rotational speed. Indicate the effective work on the graph.
3. What is the thermal power of the burner in [W]?
4. Perform the following efficiency assessment of the Stirling engine during one cycle using the effective work (Question 2) to determine:
 - Total Efficiency
 - Heater Efficiency
 - Carnot Efficiency
 - Mechanical Efficiency

Some points to explore in your discussion of Exercise A:

1. Describe the relationship between rotational frequency and exterior loads.
2. What are the differences of the real and ideal Stirling process.

EXERCISE B: MEASURING ELECTRIC POWER (SETUP #2)

PROCEDURE

1. Light the alcohol burner and after one minute, turn the flywheel to start the Stirling engine.
2. When thermal equilibrium is reached (approximately 5 minutes), record the two temperatures and rotational speed WITHOUT the transmitting belt.
3. Place the belt to the large strap wheel on the generator/motor unit carefully. DO NOT BURN YOURSELF! Record the temperatures, rotational speed, output voltage and current of the generator/motor unit on the data sheet WITHOUT LOAD (Toggle switch is in the off position).
4. Turn the switch on and the potentiometer connected to the load resistor about one turn (variable resistance) and record the temperatures, rotational speed, output voltage and current of the generator/motor unit on the data sheet.
5. Repeat by further turning the potentiometer about one turn in the same direction and record the data up to 10 turns.
6. Return the potentiometer back to its original setting.
7. Place the belt to the small strap wheel carefully and repeat the above steps. DO NOT BURN YOURSELF!
8. Turn off the alcohol burner by placing the cover over the open flame. Turn toggle switch off.

RESULTS /DISCUSSION

1. Calculate the power output of the generator/motor unit for different applied loads (i.e. at the different potentiometer settings). Show your sample calculations and tabulate all your results. Make two tables for the belt configuration.
2. Plot the electric power versus rotational speed for both wheel configurations. On the same graph, add the mechanical power data from Exercise A. Indicate on the graph the effective power for each belt configuration.

Some points to explore in your discussion of Exercise B:

1. Discuss any differences associated with the belt configuration.
2. Comparison of results with the electric generator and those obtained with the torque meter.

DATA SHEET
LAB 3: STIRLING ENGINE

EXERCISE A: MEASURING MECHANICAL POWER (SETUP #1)

Initial Burner Weight [g]: _____

Final Burner Weight [g]: _____

M [$\times 10^3$ N-m]	Speed [RPM]	T ₁ [°C]	T ₂ [°C]
0			
2.5			
5.0			
7.5			
10.0			
12.5			
15.0			

Elapsed Time [s]: _____

EXERCISE B: MEASURING ELECTRICAL POWER (SETUP #2)

Large Strap Wheel

Speed [RPM]	T ₁ [°C]	T ₂ [°C]	U [V]	I [mA]
				Without Belt
				Without Load

Small Strap Wheel

Speed [RPM]	T ₁ [°C]	T ₂ [°C]	U [V]	I [mA]
				Without Belt
				Without Load



LAB
4

REFRIGERATION TRAINER



UNIT 1: INTRODUCTION

BASIC REFRIGERATION

The main function of a refrigeration system is to remove heat from a place where heat is objectionable and transfer it to a place where it is not objectionable. This can be accomplished using four basic devices:

- Compressor
- Condenser
- Evaporator
- Pressure Reducing Device

A basic refrigeration system is shown in Figure 4.1.

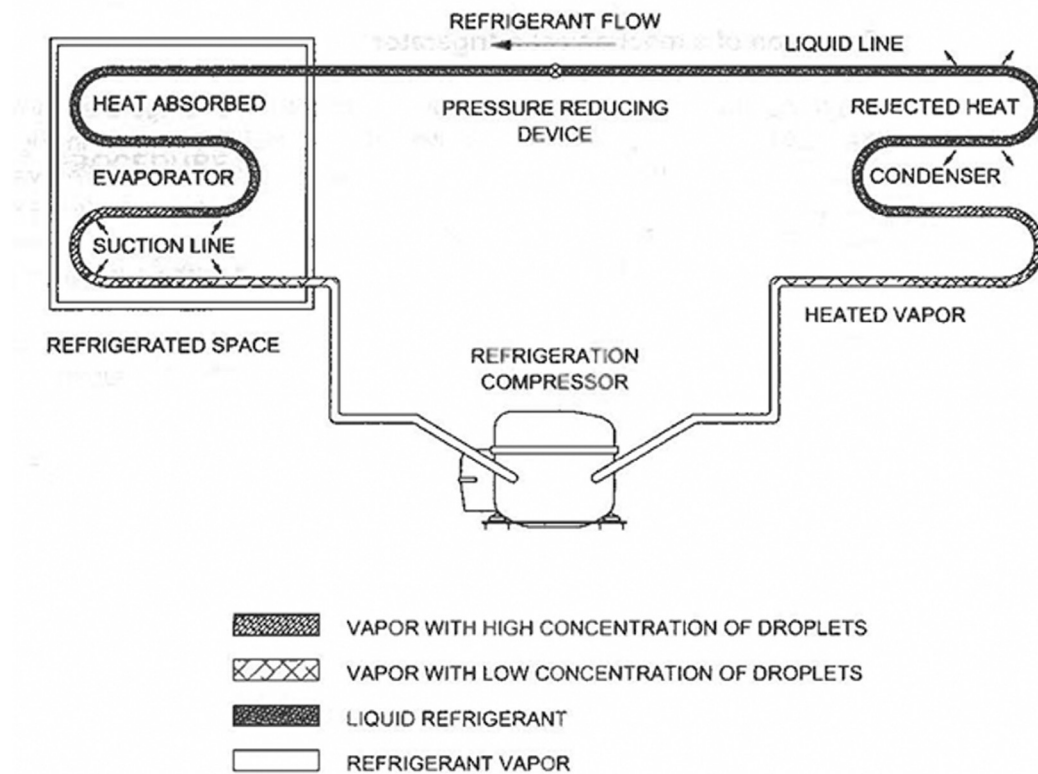


Figure 4.1: Basic Refrigeration System

The compressor is the heart of the refrigeration system. It acts as a circulating pump, drawing the refrigerant vapor from the evaporator and compressing it into the condenser.

In the evaporator, liquid refrigerant absorbs heat from the air passing over the surface of the coil. When heat is absorbed the liquid changes to vapor. The heated vapor is drawn into the compressor where it is subjected to an increase in pressure. The temperature of the vapor therefore increases.

The refrigerant vapor is now under high pressure and high temperature. The vapor now passes through the condenser where sensible and latent heat is removed and the vapor changes back into a liquid. The liquid refrigerant, however, is still under pressure.

The liquid then flows through the pressure reducing device which immediately reduces the pressure. The decrease in pressure lowers the temperature of the liquid even more.

The cold, low pressure liquid then flows through the evaporator, allowing the refrigerant to boil and vaporize, absorbing heat from the refrigerated space. The cycle then repeats as the heated vapor is drawn into the compressor.

In a refrigerator, heat is absorbed from the space to be refrigerated by evaporating the liquid refrigerant in the evaporator (cooling coil) as shown in Figure 4.2. This occurs when the refrigerant changes from a liquid to a vapor. The vapor is then pumped by the compressor into a condensing unit located outside the refrigerated space. The vapor flowing through the condenser is under a high pressure and is at a high temperature. The vapor then gives up its heat to the surrounding air. When the refrigerant has reached the end of the condenser, it has condensed into a liquid again. The liquid refrigerant then flows through the pressure reducing device into the evaporator and the cycle repeats.

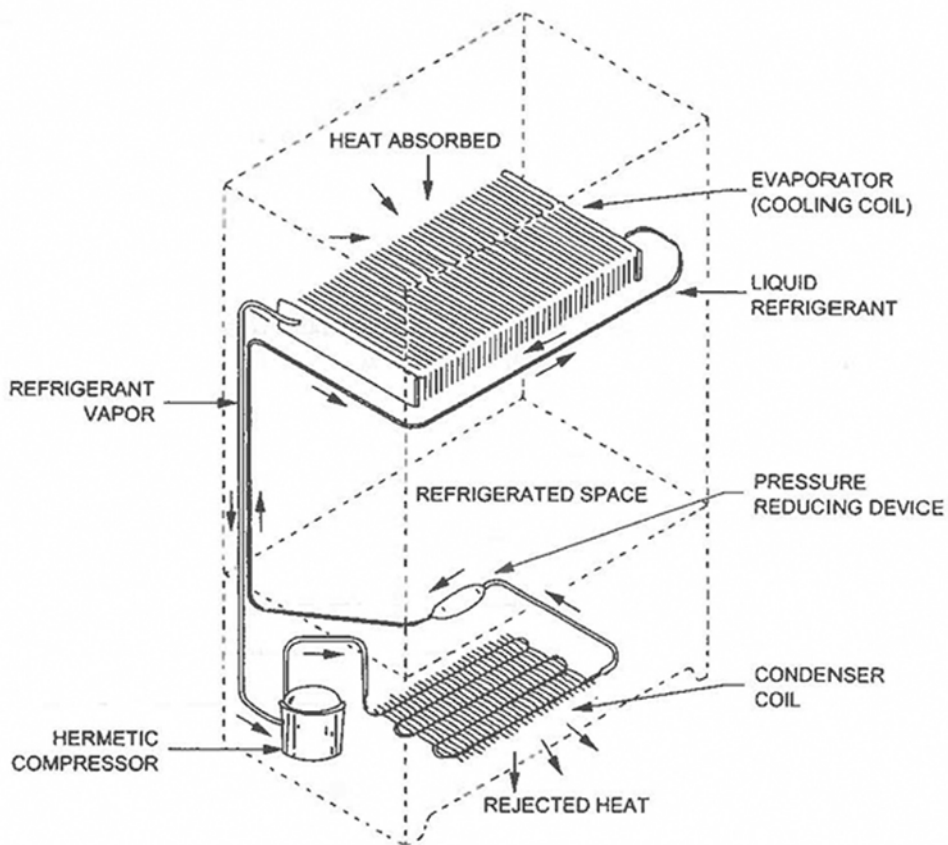


Figure 4.2: Elementary Mechanical Refrigerator

ADDITIONAL REFRIGERATION DEVICES

The basic refrigeration system in Figure 4.1 cannot efficiently operate on its own. Additional devices must be used for correct system operation. These are devices such as:

- Pressure Controllers (High and Low)
- Pressure Gauges
- Gauge Manifold
- Temperature Indicator
- Filter Dryer
- Moisture/Liquid Indicator
- Blowers and Fans
- Valves

Pressure controllers as shown in Figure 4.3 are mainly used in refrigeration systems as safety devices. They are used on both the high and pressure sides of the systems. These devices keep the system operating within design limits, by controlling pressures.

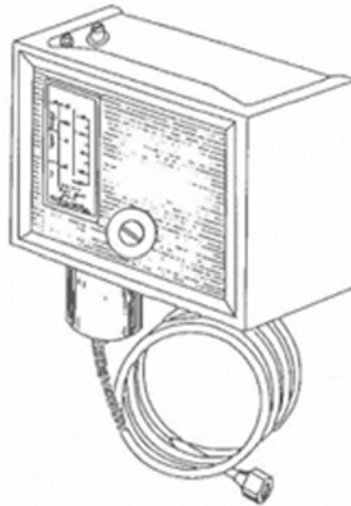


Figure 4.3: Pressure Controller

Pressure gauges are also used on both the high and low sides of the system. The pressure gauge on the pressure side is located before the pressure reducing device. The low-pressure side gauge is located after the pressure reducing device. The location of these gauges enables you to see the differential pressure across the pressure reducing device.

The gauge manifold, as shown in Figure 4.4, is mainly used for evacuating and charging the system. The two gauges mounted on the manifold are used to determine the pressure entering and leaving the compressor.

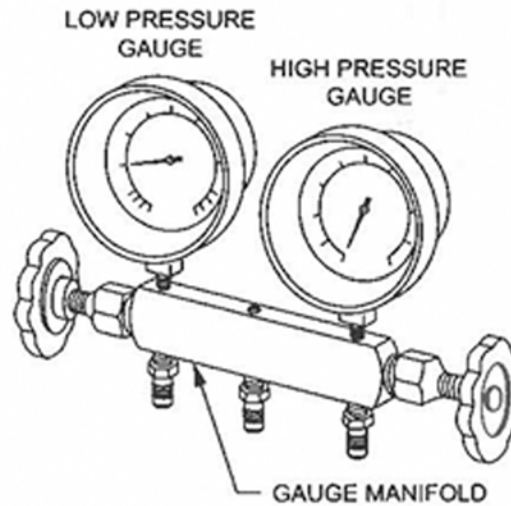


Figure 4.4: Gauge Manifold

Temperature indicators are used with temperature sensors to determine the skin temperature at various points in the system. Typical points are on the input and output of the condenser and evaporator coils.

A filter dryer, as shown in Figure 4.5, is used on the high-pressure side of the system to prevent dirt, moisture, and metal filing from entering the pressure reducing device

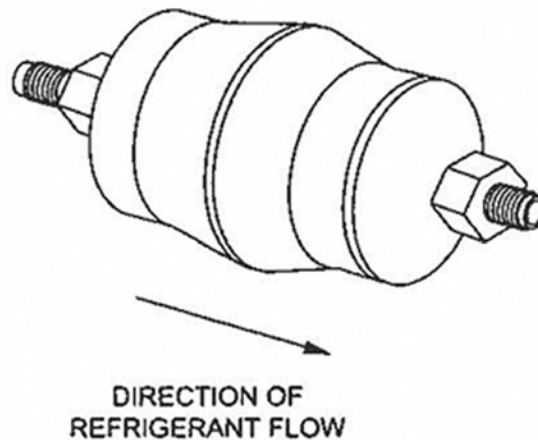


Figure 4.5: Filter Dryer

A moisture/liquid indicator, as shown in Figure 4.6, is used to indicate the flow of refrigerant in the system. Bubbles in the liquid line indicate a lack of refrigerant or restriction in the line. The indicator also shows if moisture is present in the system. Usually, dark green indicates a dry system and yellow color indicates a wet system.

An indicator is usually located after the filter dryer.

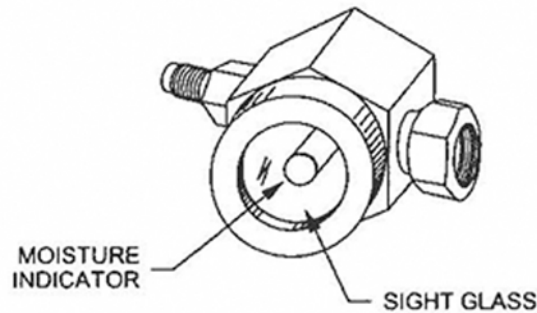


Figure 4.6: Moisture/Liquid Indicator

Blowers and fans, as shown in Figure 4.7, are commonly used in air conditioning systems. They are used to circulate air over the system refrigeration coils to help transfer heat. On a household air conditioner, a double blower with single drive motor is sometimes used.

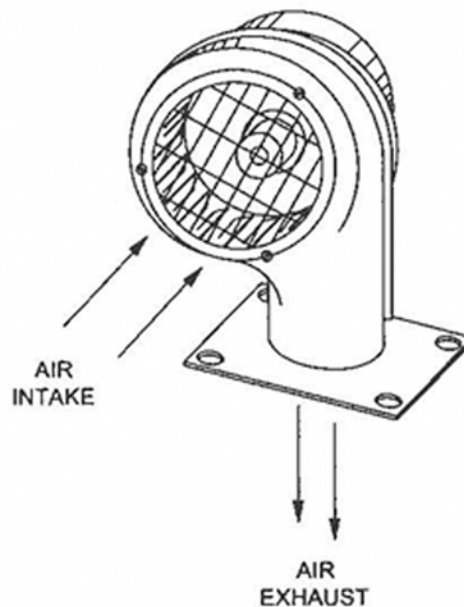


Figure 4.7: Blowers

Shut off valves are usually a diaphragm or globe type valve. The globe type valve can also be used as a manual pressure reducing device. Both valves can be in a straight through or angle type arrangement. Check valves allow fluid or vapor to flow only in one direction in a system. Check valves are often used in heat pump installations for by-passing expansion valves.

UNIT 2: COMPRESSOR

The main function of any compressor in a mechanical refrigeration system is to produce a pressure difference in the system. This creates a temperature change from one part of the system to the other. The high pressure produced by the compressor is drastically reduced by the metering device which reduces the pressure in the cooling coil.

One of the most common compressors in use today is reciprocating. This type of compressor contains pistons and operates in a manner like an internal combustion engine found in automobiles.

The number of pistons or cylinders may vary from one to as many as sixteen.

The operation of the compressor is illustrated in Figure 4.8. The passage of the refrigerant to and from the compressor is controlled by discharge and suction valves, located on a specifically designed valve plate which forms the lower part of the cylinder head.

When the piston moves away from the valve plate (down stroke), a pressure reduction takes place. Since the pressure in the cylinder is now below that in the suction line, a flow of refrigerant vapor occurs which opens the suction valve. A certain quantity of vapor refrigerant then enters the compressor.

When the motion of the piston reverses and moves towards the valve plate (up stroke), the pressure in the cylinder increases, forcing the suction valve to close. As the piston moves closer to the valve plate, the discharge valve opens and forces the refrigerant into the discharge line. This creates the high side pressure of the system.

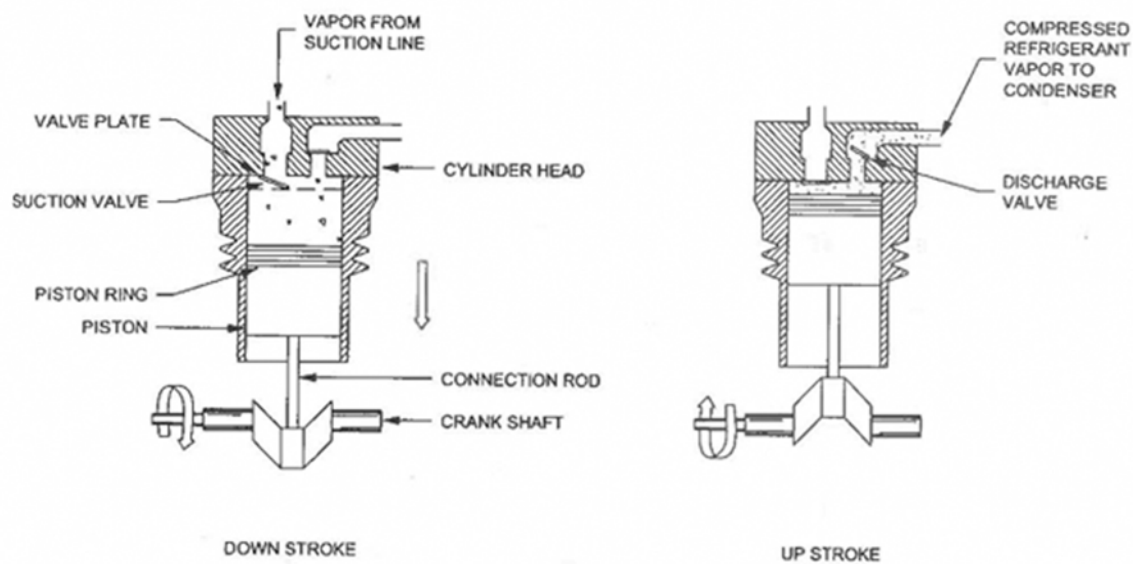


Figure 4.8: Operation of a Compressor

UNIT 3: EVAPORATOR AND CONDENSER

EVAPORATOR

An evaporator is a device (coil) in a refrigeration system that is used to absorb heat from the surrounding air or liquid, and by means of a refrigerant, removes the heat from the refrigerated area.

The liquid refrigerant, which enters the evaporator from the metering device, as shown in Figure 4.9, is at a low temperature and a low pressure. This causes the refrigerant to absorb heat from the surrounding area. The heat absorbed causes the temperature of the liquid refrigerant to increase to its boiling point (sensible heat) and further, to change into vapor (latent heat). The vapor then moves on to the suction side of the compressor. To prevent liquid refrigerant from flowing into the suction line, a suction line accumulator is sometimes used. This traps the liquid refrigerant that did not boil in the evaporator, protecting the compressor.

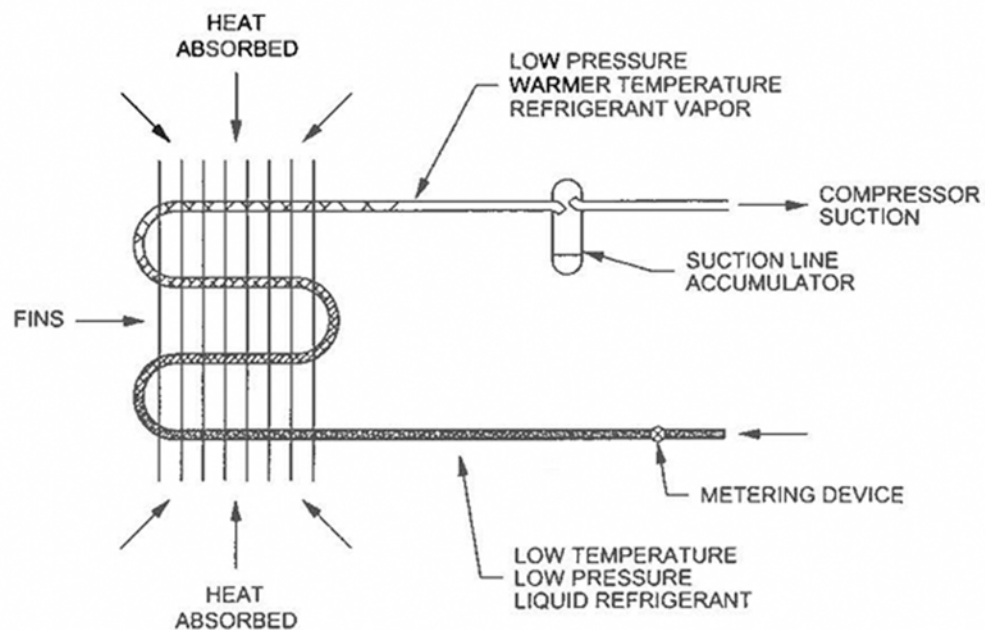


Figure 4.9: Operation of an Evaporator

The construction of evaporator coils varies greatly. Various combinations of material are used such as:

- Copper tubing and aluminum fins
- Copper tubing and copper fins
- Aluminum tubing and aluminum fins

CONDENSER

A condenser, as shown in Figure 4.10, is the device in a refrigeration system that cools super-heated, high pressure refrigerant vapor. By rejecting sensible heat and latent heat, the vapor is condensed into high pressure liquid refrigerant.

The refrigerant gives off heat in the condenser. The heat is transferred to an area having a lower temperature. The amount of heat given off is the heat absorbed by the refrigerant in the evaporator plus the heat created by the compressor during compression. The heat transfer medium can be air or water. The only requirement is that the temperature of the medium is lower than the temperature which corresponds to the condensing temperature of the refrigerant.

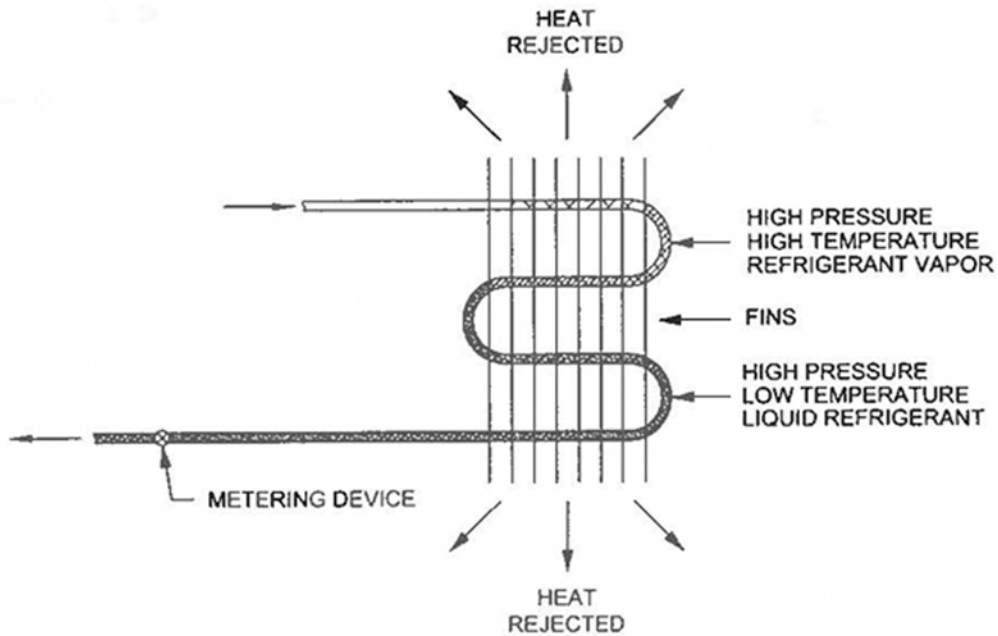


Figure 4.10: Condenser Coil

Condenser coils are basically constructed the same as evaporator coils. The various combinations of materials used for the tubing and fins are the same. The shell and tube condenser, however, is a cylinder usually inside.

UNIT 4: METERING DEVICES

CAPILLARY TUBE CONTROL

The capillary tube, as shown in Figure 4.11, is one of the most popular types of refrigerant controls. A capillary is simply a tube having a very small inside diameter with no moving parts. This tube connects the high-pressure side (condenser) of a refrigeration system to the low-pressure side (evaporator). Because of its small diameter, it must be protected by a strainer or filter dryer.

By restricting and metering the liquid flow, the capillary tube can maintain the required pressure differential between the condenser and the evaporator. The pressure drops due to friction (length of tube) and the amount of evaporation that takes place as the liquid flows through the tube. The evaporation inside the capillary is between 10 and 20% of the liquid passing through the device. The back pressure reduces the temperature of the liquid to the saturation temperature of the evaporator.

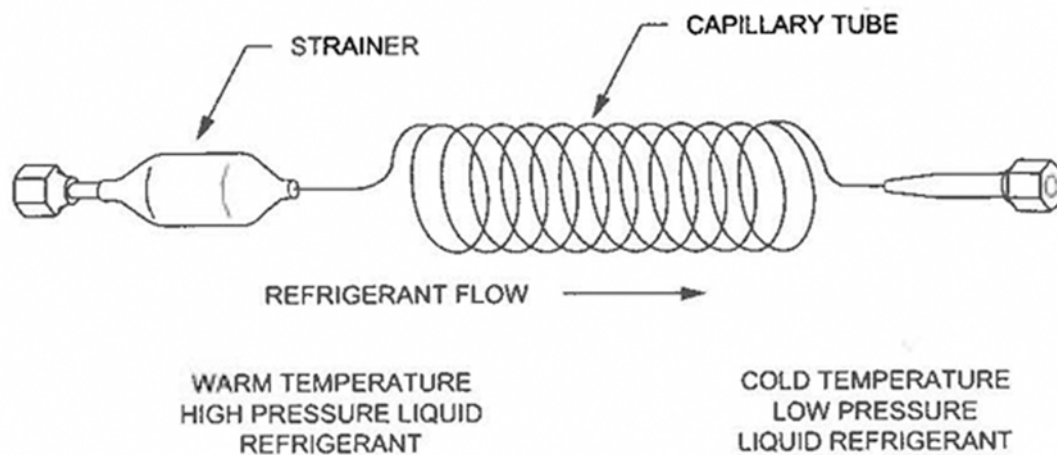


Figure 4.11: Capillary Tube Control with Strainer

The capillary tube diameter and length are very important to the pressure differential between the condenser and the evaporator. A short and small diameter tube would have the same pressure differential as a long and larger diameter tube. The main difference between the tubes is the larger diameter tube is less likely to get plugged.

The capillary tube must be such that the flow capacity must equal the compressor pumping capacity. With too great a restriction, less liquid will enter the evaporator and the excess will build up in the condenser reducing the system efficiency.

The capillary tube has many advantages such as low cost and no moving parts. Another advantage is that when the compressor stops, the pressure on both sides of the capillary tube equalizes. The system therefore has no back pressure which would cause added strain. Low starting torque motors can then be used with compressors.

THERMOSTATIC EXPANSION VALVE CONTROL

A thermostatic expansion valve, as shown in Figure 4.12, is a variable metering device used on refrigeration systems with varying loads. The metering device is used to increase evaporation with an increased load and to decrease evaporation with a decreased load.

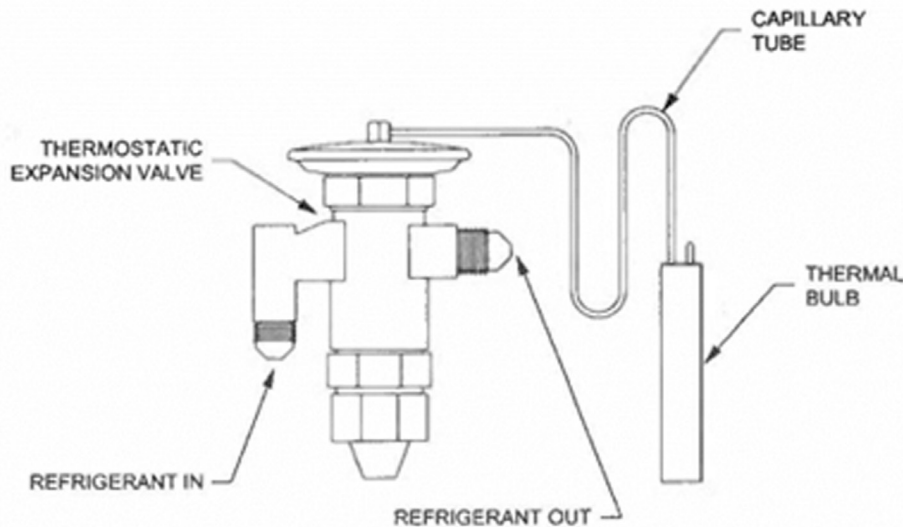


Figure 4.12: Thermostatic Expansion Valve

The internal construction of a thermostatic expansion valve is shown in Figure 4.13. The thermal bulb of the valve is partly filled with a liquid refrigerant and maintains some liquid under all conditions of temperature and load. This bulb is usually attached to the suction line of the system. Any change in temperature in the suction line will cause a corresponding change in the thermal bulb. With an increased heat load, the refrigerant in the evaporator boils away faster. This results in a rise in temperature at the thermal bulb due to super heating. The higher temperature produces an increase in pressure within the bulb and tube. This causes the metal bellows to expand and force a wider valve opening. As a result, more refrigerant is allowed to flow to the evaporator to compensate for the increased load. With a decreased load, the reverse cycle takes place.

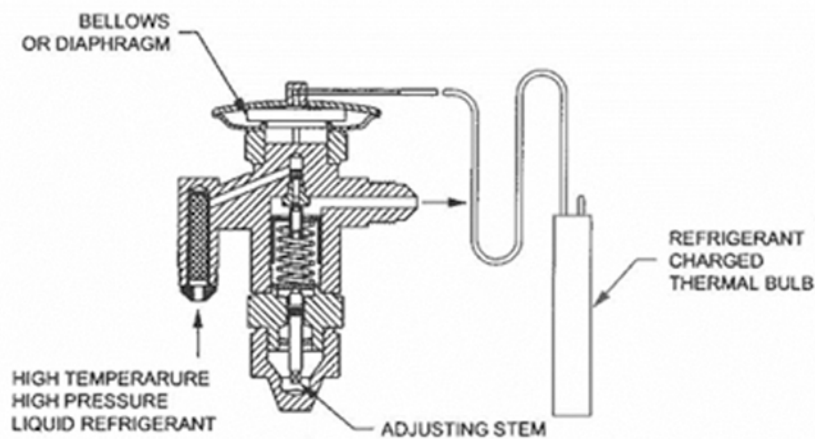


Figure 4.13: Operation of Thermostatic Expansion Valve

UNIT 5: SYSTEM CONTROL DEVICES

LOW PRESSURE CONTROLLER

Low pressure must be maintained in the evaporator for the refrigerant to evaporate. Automatic control of the compressor can therefore be based on a design pressure in the evaporator. The type of control used for this is a bellows/diaphragm operated low pressure controller. The face plate of a low-pressure controller adjusted to a typical setting is shown in Figure 4.14.

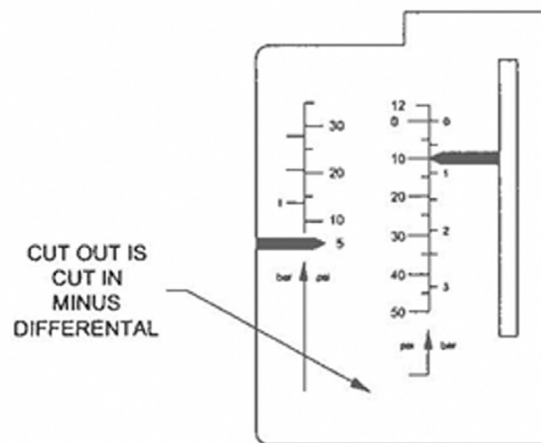


Figure 4.14: Low Pressure Controller Face Plate with Typical Setting

The low-pressure cut-off switch is connected to the low side or suction side by means of a capillary tube. When the evaporator pressure rises, the low side pressure increases above the setting of the controller, which causes an increase in pressure on the bellows of the pressure control. The bellows expand, activating a switch which starts the compressor. The compressor will run until the evaporator pressure is brought down to the preset pressure setting of the controller. A drop in pressure correspondingly reduces the pressure on the bellows. The bellows then contract, opening contacts to automatically shut off the compressor.

Low pressure controllers are used as both a safety control against pulling a vacuum, causing damage to the compressor, and as a temperature control. Since changes in evaporator temperature correspond to changes in suction pressure, the low-pressure control can indirectly be used to control refrigerated space temperatures. A thermostat can therefore be eliminated since the compressor will cut out and cut in at the set temperature and pressure. The low-pressure controller can also be set to prevent ice formation on the evaporator.

Pressure controllers usually have two main adjustments: a range adjustment and a differential adjustment. However, some controllers have factory preset settings. The range adjustment screw should be adjusted first to the design setting. The differential adjustment screw can then be set. This sets the cut-out and cut-in pressure allowance above and below the set point. Spring tension on both the range and differential screws cause travel on the bellows to increase or decrease the pressure on the bellows.

HIGH PRESSURE CONTROLLER

High pressure must be maintained in the condenser for the refrigerant to condense. Automatic control of the compressor can therefore be based on the high side of the system. The type of control used for this is a bellows/diaphragm operated high pressure controller. The face plate of a high-pressure controller adjusted to a typical setting is shown in Figure 4.15.

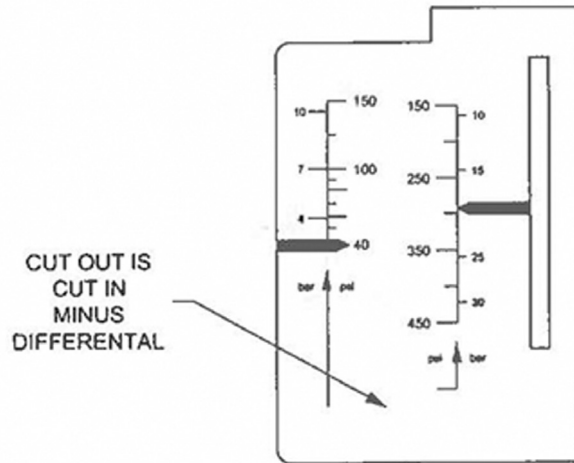


Figure 4.15: High Pressure Controller Face Plate with Typical Setting

The high-pressure controller is connected to the high side of the system by means of a capillary tube. When the condenser temperature rises, the high side pressure increases which causes an increase in pressure on the bellows of the pressure control. The bellows expand, activating a switch which shuts off the compressor. The compressor will remain off until the pressure is reduced to the required level. The drop in pressure correspondingly reduces the pressure on the bellows. The bellows then contract, closing the contact to automatically restart the compressor.

High pressure controllers are used as both a safety control. This control cycles the compressor off in the event of excessively high pressure in the system. The high pressures are caused by elevated ambient condensing temperatures and non-condensables in the system such as water vapor. The high-pressure controller operates in a similar manner to the low-pressure controller but on the high side of the system. Here the contacts open on a rise above the set point. High- and low-pressure controllers can be used together in a single refrigeration system.

High pressure controllers usually have the same two main adjustments just like the low-pressure controller.

UNIT 6: HEAT PUMP

BASIC HEAT PUMP

A basic refrigeration system rejects heat at the condenser. The amount of heat rejected is greater than the heat absorbed at the evaporator. The movement of heat makes it possible to use a refrigeration system for heating. This type of system is called a heat pump. The term heat pump is applied to systems that provide both cooling and heating. In a heat pump system, two refrigerant metering controls and a reversing mechanism must be added to the basic refrigeration system.

The cooling cycle produces a cooling effect in the same manner as the basic refrigeration system. To produce a heating effect, the flow of refrigerant must be reversed. This is done using a 4-way reversing valve. The valve reverses the flow of refrigerant to the evaporator and condenser. However, the flow of refrigerant through the compressor must always remain the same.

Four manual valves are used to simulate this flow reversal on the Refrigeration Demonstrator.

A heat pump in the heating cycle is shown in Figure 4.16. During this cycle, the evaporator (indoor coil) operates the same as a condenser, and the condenser (outdoor coil) operates the same as an evaporator. Liquid refrigerant enters the outdoor coil and absorbs heat from the surrounding outside air. The refrigerant vaporizes and is drawn into the compressor. The vapor is compressed, increasing its temperature, and is pumped into the indoor coil. Since the vapor temperature is higher than the indoor temperature, heat will be released into the room.

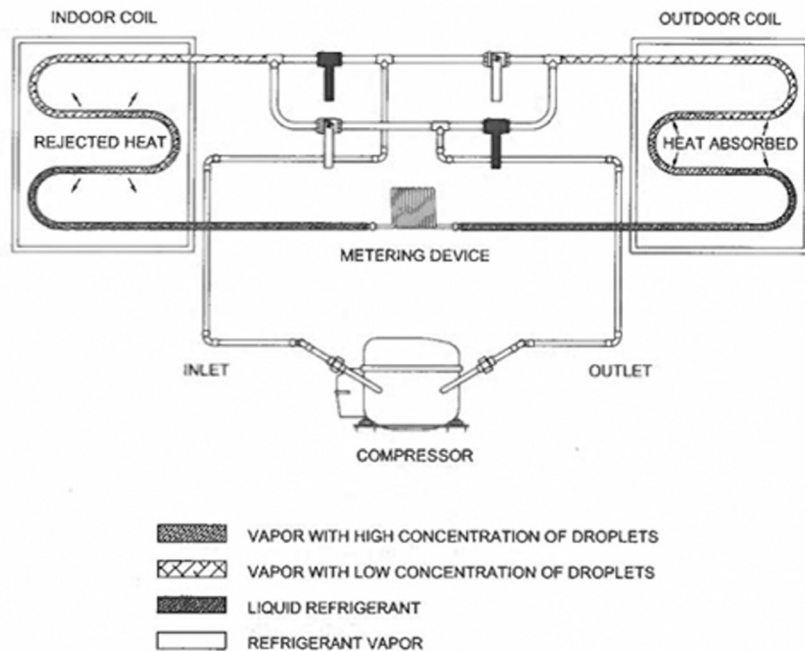


Figure 4.16: Heat Pump on Heat Cycle

REVERSING REFRIGERANT FLOW

To reverse the direction of refrigerant flow in a refrigeration system, a 4-way reversing valve, or four manual valves can be used.

The 4-way reversing valve, as shown in Figure 4.17, is operated by pressure. A solenoid valve controls the pressure in the pilot valve when the solenoid is energized. The low side pressure lifts or slides the plunger to place the system in heating mode. Once the solenoid is de-energized, the high side pressure moves the plunger back, returning the system to the cooling mode.

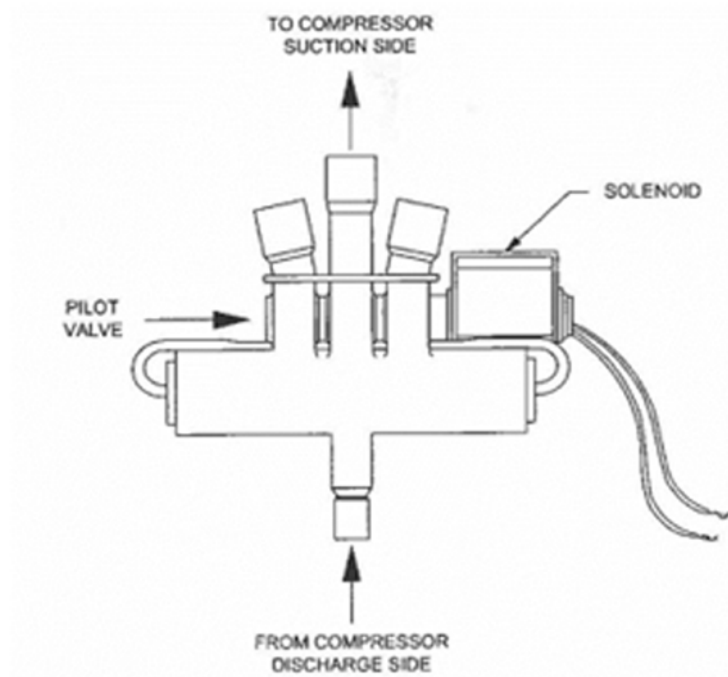


Figure 4.17: 4-Way Reversing Valve

Four manual valves can also be configured to reverse the direction of refrigerant flow. This method however is not commonly used in industry. The four manual valves in Figure 4.18 are configured to provide cooling. Refrigeration Demonstrator valves V4-B and V4-C are closed, and valves V4-A and V4-D are open.

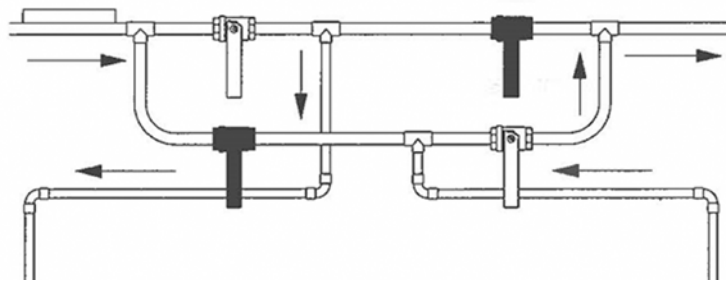
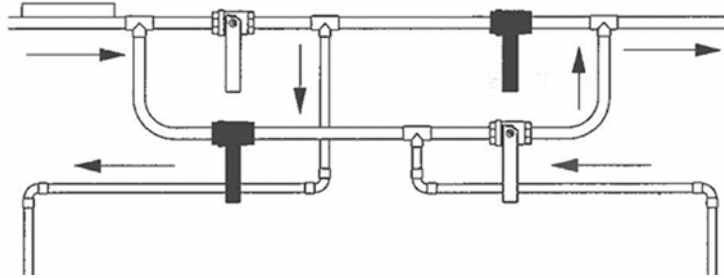


Figure 4.18: Four Manual Valves Set to Cooling Mode

To reverse the direction of refrigerant flow, Refrigeration Demonstrator valves V4-B and V4-C are open and valves V4-A and V4-D are closed, as shown in Figure 4.19. Note the direction of refrigerant flow

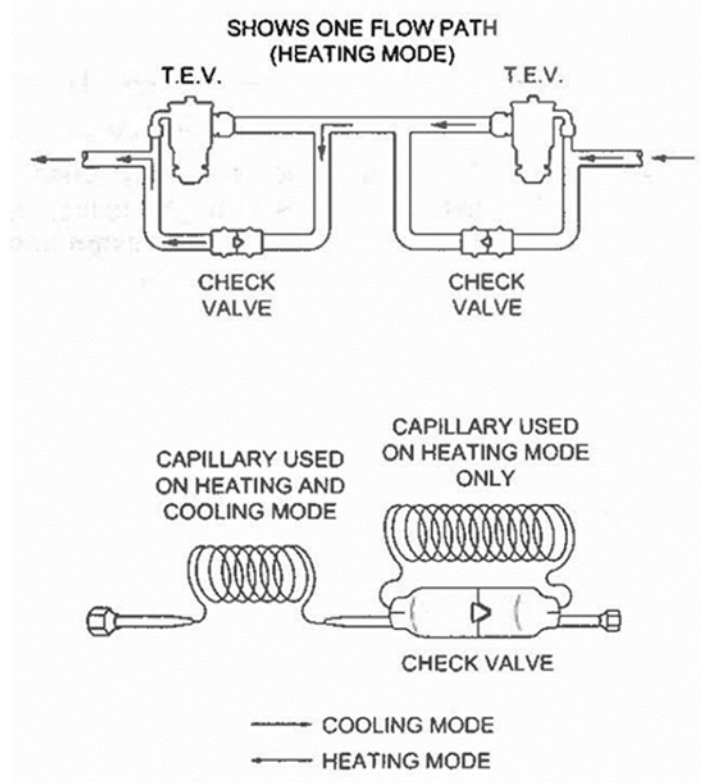


through the compressor remains the same.

Figure 4.19: Four Manual Valves Set to Heating Mode

HEAT PUMP CONTROL

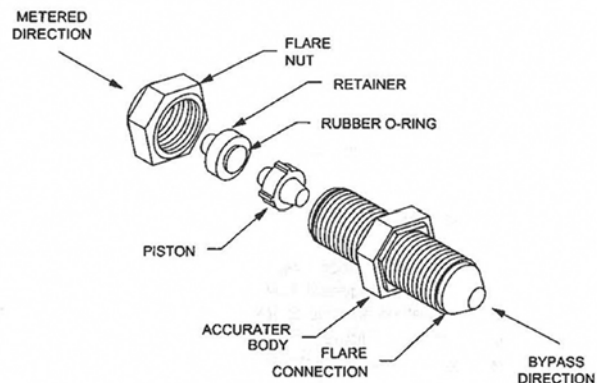
Controls for refrigerant systems with reversible heat pump applications must have provisions for refrigerant flow in both directions. To do this, two thermostatic expansion valves and two check valves, or two capillary tubes with check valves are used as shown in Figure 4.20. Check valves are used to bypass one thermostatic expansion valve depending upon the cycle in operation since one or the other



will restrict the refrigerant flow.

Figure 4.20: Heat Pump Refrigerant Control Using Capillary Tube with One Check Valve and Thermostatic Expansion Control with two Check Valves

Another method of metering refrigerant flow in heat pump system is using the two combined check valve and expansion device assemblies called Accurater™. Accurater™ provides refrigerant metering in one direction and a bypass in the other direction. Two Accuraters™ are used to provide metering in any



cycle of operation. A disassembled Accurater™ is shown in Figure 4.21.

Figure 4.21: Accurater™ (Courtesy Carrier)

The Accurater™ is made up of a body, piston, retainer, O-ring, and flare connections. The piston has a hole through it to provide refrigerant metering in one direction. The retainer forms a stop for the piston in the refrigerant bypass mode and a sealing surface for the flare connection.

REFERENCES

- Lab-Volt, Refrigeration Fundamentals, First Edition, 1997.

DELIVERABLE

Answer all questions in the handout given in the laboratory by the lab instructor and submit at the end of the lab period. There is NO lab report to submit in two weeks.

Faculty of Engineering and Computer Science Expectations of Originality

This form sets out the requirements for originality for work submitted by students in the Faculty of Engineering and Computer Science. Submissions such as assignments, lab reports, project reports, computer programs and take-home exams must conform to the requirements stated on this form and to the Academic Code of Conduct. The course outline may stipulate additional requirements for the course.

1. Your submissions must be your own original work. Group submissions must be the original work of the students in the group.
2. Direct quotations must not exceed 5% of the content of a report, must be enclosed in quotation marks, and must be attributed to the source by a numerical reference citation¹. Note that engineering reports rarely contain direct quotations.
3. Material paraphrased or taken from a source must be attributed to the source by a numerical reference citation.
4. Text that is inserted from a web site must be enclosed in quotation marks and attributed to the web site by numerical reference citation.
5. Drawings, diagrams, photos, maps or other visual material taken from a source must be attributed to that source by a numerical reference citation.
6. No part of any assignment, lab report or project report submitted for this course can be submitted for any other course.
7. In preparing your submissions, the work of other past or present students cannot be consulted, used, copied, paraphrased or relied upon in any manner whatsoever.
8. Your submissions must consist entirely of your own or your group's ideas, observations, calculations, information and conclusions, except for statements attributed to sources by numerical citation.
9. Your submissions cannot be edited or revised by any other student.
10. For lab reports, the data must be obtained from your own or your lab group's experimental work.
11. For software, the code must be composed by you or by the group submitting the work, except for code that is attributed to its sources by numerical reference.

You must write one of the following statements on each piece of work that you submit:

For individual work: **“I certify that this submission is my original work and meets the Faculty's Expectations of Originality”**, with your signature, I.D. #, and the date.


For group work: **“We certify that this submission is the original work of members of the group and meets the Faculty's Expectations of Originality”**, with the signatures and I.D. #s of all the team members and the date.

A signed copy of this form must be submitted to the instructor at the beginning of the semester in each course.

I certify that I have read the requirements set out on this form, and that I am aware of these requirements. I certify that all the work I will submit for this course will comply with these requirements and with additional requirements stated in the course outline.

Course Number: MECH 351 _____ Lab Section: _____
Name: _____ I.D. #: _____
Signature: _____ Date: _____

¹ Rules for reference citation can be found in “Form and Style” by Patrich MacDonagh and Jack Bordan, fourth edition, May, 2000, available at <http://www.encs.concordia.ca/scs/Forms/Form&Style.pdf>.



IN CASE OF EMERGENCY REMAIN CALM

AND FOLLOW THESE INSTRUCTIONS

Fire/Evacuation



Fire:

- If you see smoke or fire activate the nearest fire alarm.

Evacuation:

- Stay calm; do not rush or panic
- Safely stop your work,
- Gather your personal belongings; coat, purse, etc...
- Close and lock your door and windows.
- Use stairs only; do not use elevators or escalators,
- Once outside, move away from the building.
- Do not re-enter the building until instructed to do so by Security.

Shelter In Place



Communication:

- Shelter-in-Place will be announced by intercom P.A. voice communication, text messaging,
- Fire alarms will not be sounded.

Procedures:

- Lock classroom, office and lab doors if possible, remain quiet and do not enter the hallway,
- Should the fire alarm sound, DO NOT evacuate the building unless:
 1. You have first hand knowledge that there is a fire in the building,
 2. You are in imminent danger, or
 3. You have been advised by Security or Police to evacuate the building.
- Crouch down in the areas that are out of sight from doors and windows,
- Anyone in the hallways are to seek shelter in the nearest classroom,
- Anyone outdoors on campus should immediately take cover,
- If safe you can call 514-848-(8800) for more information on the situation.

Suspicious Person/Package



Suspicious Person:

- Do not physically confront the person,
- Do not let anyone into a locked building/office,
- Call Security @ 514-848-(3717),
- Provide as much information as possible about the person and his or her direction of travel.

Suspicious Package:

- Do not touch or disturb object,
- Call Security @ 514-848-(3717),
- Notify your Supervisor.

Medical Emergencies



- In the event of a serious or life threatening injury or illness;
- From a safe location; call Security immediately at 514-848-(3717),
- Ensure your personal security before attempting first-aid,
- Provide the victim appropriate first-aid & comforting,
- Do not give the victim anything to drink or eat.

**If the injury is the result of a fall or significant trauma:
Do not move the victim unless absolutely necessary.*

Hazardous Materials



- If an emergency develops or if anyone is in danger, call 514-848-(3717),
- Move away from the site of the hazard to a safe location,
- Follow the instructions of Emergency Personnel,
- Alert others to stay clear of the area,
- Notify Emergency Personnel if you have been exposed to the hazard or have information about the release.

Power Failure



- Remain calm and move cautiously to a lighted area,
- Do not evacuate unless asked to by Emergency Personnel,
- Do not use candles!
- For localized outages, contact Security at 514-848-(3717).



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