FROM HEAT PUMPS TO HURRICANES: APPLICATION OF THERMODYNAMICS IN SECONDARY EDUCATION

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ABSTRACT

A short teaching unit was devoted to explore and understand the physics behind some natural phenomena and devices the operation of which are connected to thermodynamics. Besides to deepen the students' knowledge of thermodynamics, the aims were to raise their interest, to enhance collaborative work, and to emphasize the importance of environmental mindedness. In the present paper the main discussion points of the teaching unit and the experiences gained during the lessons and afterwards are presented.

INTRODUCTION

The students' decreasing interest for physics is a major problem of physics teaching, and physics teachers worldwide seek the possibility for the change of this tendency [1, 2]. In our opinion the investigation of the physics of the devices used in everyday life might be a good tool for this. Thermodynamics gives a lot of opportunities to raise the interest of students. The basis of the operation of many appliances and machines, (e.g.: refrigerator, air conditioner, heating systems of houses, engines of cars, jets etc.) and even a natural phenomenon, the hurricane can be discussed by some kind of thermodynamic cycles.

With one of my groups of students I spent 8 extra lessons to teach the thermodynamic background of some technical devices and the tropical cyclones. The aim on one hand was to raise the interest of the students. On the other hand, it gave the possibility to address the environmental issues as well. The students had to work in groups, they had to do some research on how the chosen device worked, and they also had to give an oral presentation to their classmates about what they learnt. Finally a questionnaire was given to them, in order to find out how much they learnt.

BACKGROUND AND TASK

In the academic year of 2014-15 I taught the first year of a 2-year preparatory physics course for the University. (The time allocation of the course was four 45-minute lessons per week.) Part of the course was to introduce the students the basics of thermodynamics: gas laws, kinetic gas model, processes (isothermal, isobaric, isochoric and adiabatic) and cyclical processes (including the terms efficiency and COP), and the laws of thermodynamics.

Two 45-minute lessons were spent on the thorough discussion of the idealised cyclic processes of the two most common car engines, the Otto and the Diesel engines.

The Otto cycle is easier, after introducing the equation of the adiabat the efficiency ($\eta = 1 - \left(\frac{V_2}{V_1}\right)^{\kappa-1}$, where V_1 and V_2 are the bigger and smaller volumes of the working substance, respectively, and κ is the ratio of specific heats) of the idealised cycle was derived.

Although the derivation needs some mathematical skills, (maybe in the case of a less able group it can be omitted) but the result is quite simple and it enables us to explain the terms compression ratio ($\frac{V_2}{V_1}$), octane number and the role of the spark plug. The calculation of the efficiency of the ideal Diesel cycle is a bit more demanding, so its formula was just stated, in order to show that (among other factors as well) it also depends on the compression ratio of the working substance [3]. Students can easily understand it, since in the case of Diesel engines air is compressed instead of the air–gasoline mixture, it is more compressible, therefore Diesel engines have greater efficiency. Students can also realise that these engines are heavier because for the greater compression stronger piston walls are needed.

Besides the discussion of the operation of these engines it is also substantial to explain the environmental impact of these engines. Students could be explained to that although Diesel engines have greater efficiency than Otto-engines, their exhaust fumes are more dangerous, because they contain more Nitrogen-oxides and particulate matter, which are both harmful pollutants [4]. After this introduction, students were given the task to research different devices which are operated either as a heat engine or a heat pump. They were given two weeks to work in groups and prepare for their presentations (as homework). Four 45-minute lessons were spent on discussion of these devices, and where it was relevant the environmental issues were addressed as well.

OTHER TWO HEAT ENGINES (EXPLAINED BY STUDENTS)

Two groups of students researched and made presentations about heat engines, one was the Wankel engine, and the other was the Stirling engine. Both groups found interesting details on the operations of the engines, and showed videos (found on the internet) to illustrate their operation.

Wankel engine is a spark ignited engine but it works differently from the usual four-stroke engines. Its common name is rotary engine, since the piston is rotating in an eccentric shaft. Its advantages are that it is small and simple, it has high power to weight ratio. Its disadvantages are that it needs frequent service, it has higher fuel consumption and its exhaust is harmful. The Japanese factory Mazda manufactures cars with this type of engine [5].

Stirling engine is a well-known engine among physics teachers, but not for the ordinary people. It is important because it is an external combustion engine, so it can be operated with any heat source, thus it can be more environmental friendly if the burning process of the fuel is complete. It has high efficiency, but less than the Carnot efficiency [6, 7], (this is stated wrongly in many cases) since the cyclical process consists of two isotherms and two isochors (and not two adiabats). Some disadvantages of this engine are for example that it is big and slow to ignite.

HEAT PUMPS

Before the discussion of heat pumps, it was recalled that heat pumps are reversed heat engines. The schematic figure of heat pumps is shown in Fig.1, where Q_C is the heat released by the cold heat reservoir, Q_H is the heat absorbed by the hot reservoir and W is the external work done.

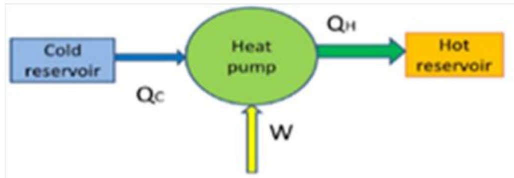


Fig.1. Schematic figure of a heat pump

Their "efficiency" is characterised by the so called coefficient of performance (abbreviated as COP). It was also pointed out that this COP is defined differently if the heat pump is used for heating or if it is used for cooling, depending on what is useful for us.

$$COP_{Heating} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} > 1 \tag{1}$$

$$COP_{Cooling} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C} \tag{2}$$

Taking away (2) from (1) it can be seen that if the same heat pump is used for heating and for cooling, the difference between its COP values is one. In this sense heating is more efficient than cooling [8].

REFRIGERATORS AND HVAC (HEATING, VENTILLATING AND AIR CONDITIONING) DEVICES (STUDENT'S EXPLANATIONS)

For the technical application of heat pumps students found many different devices like refrigerators, the phase-change cooling system of computers, air conditioners, tumble dryers, and the different source heat-pump systems to heat buildings. In this paper only the refrigerators and the heating of buildings are presented.

The most widely used heat pump, which was developed first (more than a century before the first heat pump was used for heating) is the refrigerator. Students introduced the main ideas of both the vapour compression and the gas absorption type refrigeration systems. Although the cyclic process of the refrigerant is too difficult (in both cases), the essence that the refrigerant periodically evaporates and condenses in order to absorb heat from the evaporator and then to release heat in the condenser can be understood well. In the case of the compression type refrigeration system the evaporated refrigerant is compressed by an electrically powered compressor, so the cooling cycle can be repeated. In the case of the absorption type system the evaporated refrigerant is absorbed by some salt solution. This refrigerant-saturated absorber must be heated, in order that the refrigerant evaporates out, and in the heat exchanger it can condense again. Since the vapour compression refrigeration system has greater COP, it is more widely used, but the other is quieter, and can be operated with any type of heat like waste heat or solar power, and not just electrical energy.

The first practical heat pump system which was used for heating was proposed by Lord Kelvin in the 19th century, but heat pumps used for the heating of buildings were only introduced in the 20th century [8]. The operation of heat pumps that are used for domestic heating and air conditioning is similar to the operation of refrigerators. The great majority of these devices are vapour-compression systems. HVAC devices are usually classified according to their heat source: there are air, ground (sometimes called geothermal) and water source heat pumps.

Air source heat pumps are the cheapest, and most commonly used as air conditioners. They can also be used for heating, but since the temperature of air in winter can be very cold, the COP of these heat pumps decreases in the coldest days of the winter. Another disadvantage is that it may be noisy.

Ground source systems are stable, but far more expensive. Fig. 2 left panel shows the sketch of two types of ground source heat pumps. Either long horizontal trenches are dug (the total area where the collector pipes are laid is approximately 2-3 times of the area which is to be heated), or vertical boreholes are drilled (60-100 m deep). Both have COP approx. 4-5.

Fig.2. Left panel: Ground source heat pumps. Right panel: Water source heat pumps

Fig.2. right panel shows the two types of water source pumps. The first extracts the heat of the ground-water. (Two wells must be drilled, one is the source from which water is pumped up, and the other is the sink, into which the cooled water flows back.) This is the most efficient of all with a COP value of 5-7, but not the cheapest, the open-loop circuits need maintenance;

ground-water must be filtered. (In Hungary the Hotel Stáció near Vecsés is equipped with this type of HVAC system.) The last figure shows a system in which heat is extracted from a river or a lake, it is less disruptive than ground source, but the open-loop type may be cut-out in winter.

A simple estimation can be made for the COP of these systems. As an example consider the shallow vertical ground source system. It extracts heat from the ground at a temperature of 10°C and it releases it to the room at a temperature of 20°C. If the Carnot cycle's COP is used for the estimation we gain $COP_{Carnot} = \frac{293}{293-283} = 29.3$. In reality the heat pump is operated not between the heat reservoirs of temperatures 10°C and 20°C, but between colder and warmer ones. If the ground is at a temperature of 10°C the trench temperature is approximately 4 °C, the temperature of glycol which is flowing in the collector pipes may be at -1°C. The refrigerant temperature in this case might be only -10°C. Similarly in order that the radiators release heat to the room at a temperature of 20°C, the radiators must be warmer, let us estimate with 50°C, and the condensing temperature of the refrigerant must be even higher, approximately 60 °C. Again approximating the cyclic process of the heat pump with the Carnot COP, but using the -10°C and 60°C temperature values, we gain a much smaller coefficient of performance: $COP= \frac{333}{333-263} = 4.75$. (These estimations were not calculated by the students, but not too difficult to understand.) [9] What is important to realise, is that heat pumps perform better if the difference between the temperatures of the hot and cold reservoirs is smaller. It means that in the case of domestic heating large heat exchangers are better, therefore wall or underfloor heating should be used rather than radiators.

ENVIRONMENTAL ISSUES TO DISCUSS

Heating with heat pumps is regarded as an environmental friendly way of heating, since it is considered a low carbon technology, but we should be careful. To operate the heat pump we (usually) need electricity, so the carbon emission of the heat pump also depends on how electricity was generated. The installation of the heat pump should be carefully planned, otherwise it may happen that the heat source gets exhausted of heat, its temperature decreases, thus the COP of the heat pump decreases as well, and it uses more energy.

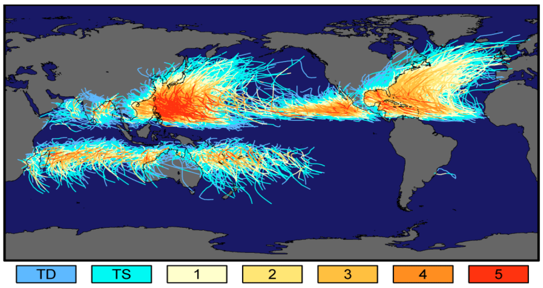
Another important factor that scientists and engineers must consider is the question of refrigerants. In the beginning of the last century chlorofluorocarbons (CFC) later hydro-chlorofluorocarbons (HCFC) were used, but they caused the depletion of the ozone layer of the Earth. Now the most common refrigerants are hydrofluorocarbons (HFC), which do not ruin the ozone layer, but have very big global warming potential. (Approximately 1550 times as much as that of carbon dioxide.) Hydrocarbons (HC), ammonia (NH_3) or carbon dioxide (CO_2) can also be used as refrigerants, but unfortunately HCs are flammable, NH_3 is toxic, and CO_2 is not as efficient as the others [9].

NATURE'S HEAT ENGINE

Finally during two lessons the physical background of tropical cyclones were explained to the students. For the explanation of the formation of hurricanes, the Coriolis force was introduced to the students, and then the necessary conditions for Tropical cyclone genesis were explained [10]. (These are the following: at least 27˚C sea-surface temperature; instability of the air; high relative humidity, it should be at least 500 km away from the equator; surface vorticity; weak vertical wind shear.)

Fig.3. left panel shows the tracks and intensities of tropical storms observed between 1851 and 2006. It can be seen in the figure that there are no hurricanes close to the equator, because the Coriolis force is not big enough to make the air rotate. Also the already formed hurricanes never cross the equator.

The structure of a hurricane is shown in Fig. 3 right panel. If somewhere above the sea there is a depression, then air begins to flow there and then it rises. While the hot humid air rises, it expands and should cool down, but also the water precipitates and rains out, which warms back the air in the eye of the hurricane. The air which flows in above the sea, is rotated by the Coriolis force, in the Northern hemisphere in counter-clockwise direction, while at the top of the hurricane the air spreads out and is rotated in the opposite direction. In the figure it can also be seen that in the eye of the hurricane air is descending whilst in the eyewall it ascends. The heaviest storms occur in the eyewall, while in the eye there is neither wind nor rain. The regions in which air ascends and descends vary almost periodically in space.



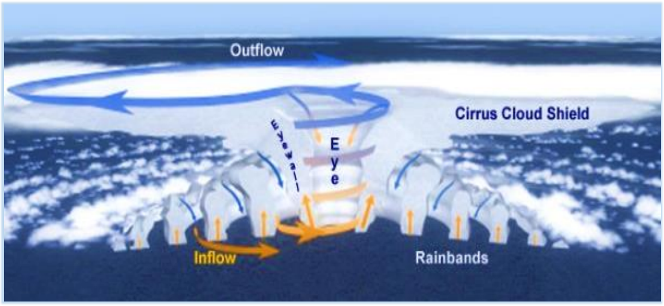
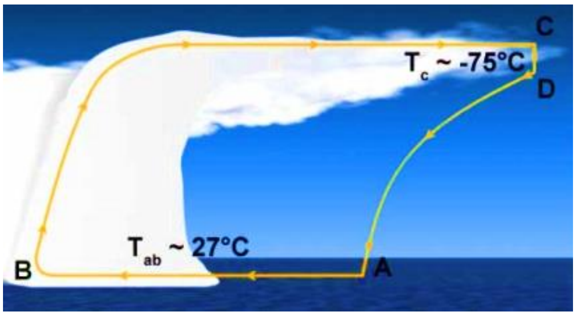


Fig.3. Left panel: Tracks and intensities of tropical storms (TD: tropical depression; TS: tropical storm; tropical cyclones are numbered from 1 to 5 in the order of increasing strength.) (source [11]), Right panel: Structure of a hurricane (source [11])

Meteorologists approximate the cyclic process of the hurricane as a Carnot cycle. The left panel of Fig.4. shows the ideal Carnot cycle of hurricanes, whilst on the right panel the p-V diagram of the cycle is indicated.



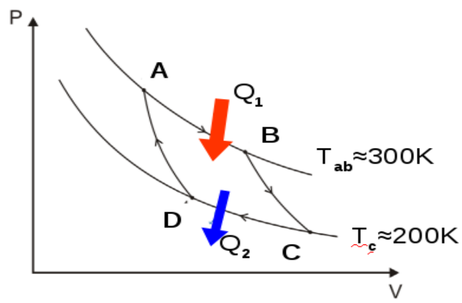


Fig.4. Left panel: the Carnot cycle of hurricanes (in space). (source [11]),
Right panel: the p-V diagram of the Carnot cycle

The processes can be described as follows: A→B (isothermal process): the warm surface of the ocean keeps the air at approximately constant temperature, which begins to flow towards the centre of the hurricane. B→C (adiabatic process): the saturated air begins to rise. During the adiabatic ascent, the air cools down and the water precipitates and rains out. When water changes from the gaseous to the liquid state heat is released, thus the centre of the cyclone remains hot. The ascent of air slows down and the air spreads out and gets far from the core of the cyclone. C→D (isothermal process): the temperature of the air is approximately constant in this zone; the air descends and gives off heat. D→A: adiabatic descent of air. After the explanation my students could easily calculate that the efficiency of the Carnot cycle of tropical storms is 1/3.

ASSESSMENT

At the end of the 8-hour teaching unit the students were given a questionnaire. In the first part the students were asked true-or-false questions based on the covered topics. (There were eight groups of questions, each containing 3 or 4 questions.) The percentage value of the number of students who answered correctly to each question is shown in Fig.5.

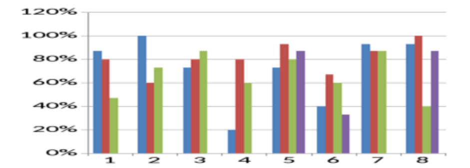


Fig.5. Percentage values of correct answers for the questions

As examples here are some of the questions: (the percentage values after them indicate the ratio of students who answered the question correctly)

2. c) In Diesel engines the pure air is compressed. (True) 73%
5. d) If the same heat pump can be operated in order to cool down and to heat up the room, then its COP is greater when it is used for cooling. (False) 87%
5. c) In the case of the gas-compression type refrigerators the condensing refrigerant absorbs heat from the environment. (False) 80%
6. d) In a hurricane the ascending wet air condenses and heats up the ambient air. (True) 33%

The second part of the questionnaire aimed to find out the students' opinion about the project. They had to give marks from 1 to 5 for the following questions: (1 meant disapproval, and 5 approval; each number after the question indicates the average of the given marks.)

Did you find it useful to prepare for your oral presentation? 4.46
Did you find the presentations useful? 4.15
Did you find the presentations interesting? 4.31
Did you learn from the presentations? 3.69
Would you like to learn this way in the future? 3.42

CONCLUSIONS

A new short teaching unit was elaborated for teaching the basis of thermodynamics with particular regard to its technical applications, and the environmental impact of the applications. The main purpose was to raise the student's enthusiasm to learn physics. The students worked in groups and researched different devices, and finally gave short presentations on their results. Most of the students were enthusiastic, inquiring, and enjoyed the lessons. The topics were worth discussing. Quite understandably the students found their own presentations the most useful, and probably they learnt the most from these. They also found the presentations interesting, but found a bit more difficult to learn from their classmate's ones. It can be seen that the idea of efficiency and COP, (particularly that of the Carnot cycle) has a central part in understanding the operation of the household technical units. However, in numerical calculations students need a bit more feedback and guidance to be able to apply these ideas independently.

REFERENCES

1. M. O. Martin, et al.: TIMSS 2011 International Results in Science, TIMSS & PIRLS International Study Center, Lynch School of Education, Boston College, Chestnut Hill, MA, USA (2012)
2. M. Volná, et al.: Modern Tools For Popularization and Motivation Students in Physics Teaching, Problems of Education in the 21st Century 31, 112-118, 2011
3. H. B. Callen: Thermodynamics, Wiley, New York, 1960 p. 357
4. I. A. Reşitoglu, et al.: The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems, Clean Techn Environ Policy 17, 15–27 (2015)
5. https://www.youtube.com/watch?v=sd6pJtR4PaY
6. http://www.pha.jhu.edu/~broholm/l39/node5.html
7. http://ttomc.elte.hu/kiadvany/fizika-tanitasa-kozepiskolaban-i
8. D. A. Reay and D. B. A. Macmichael: Heat Pumps, Pergamon, Oxford, 1988
9. J. Cantor: Heat pumps for the home, The Crowood Press, Ramsbury, 2011
10. K. A. Emanuel: The Theory of Hurricanes, Annu. Rev. Fluid Mech. 23, 179-196, 1999
11. http://www.meted.ucar.edu/tropical/textbook_2nd_edition/media/graphics/