Journal of Technology and Science Education

MASS, ENERGY, ENTROPY AND EXERGY RATE BALANCE IN A RANQUE-HILSH VORTEX TUBE

Edorta Carrascal Lecumberri, José María Sala Lizarraga
Department of Thermal Engineering. University of the Basque Country
edorta.carrascal@ehu.es

Received July 2013
Accepted September 2013

Abstract

The objective of this paper is to present a laboratory program designed for the Thermodynamics course offered in the Department of Thermal Engineering at the University of the Basque Country. With reference to one of the examples given in the textbook by Moran, Shapiro, Boettner and Bailey (2012), the balances of mass, energy, entropy and exergy are applied to a particular control volume, and the ideal gas model is used.

Using a Ranque-Hilsh vortex tube (Ranque, 1934), the division of a compressed air flow into two streams at a lower pressure is achieved: one hot stream, where the temperature can exceed 100 °C, and another cold stream, in which temperatures can fall below -40 °C. Therefore, an air flow is divided into two separate hot and cold streams, without any thermal interaction with hot or cold focuses.

The vortex tube is used to demonstrate the basics of the First and Second Law of Thermodynamics. In addition, this practical laboratory program can even be used to make sense of one of the best-known theoretical experiments in thermodynamics, the so-called Maxwell's demon experiment (Lewins & Bejan, 1999; Liew, Zeegers, Kuerten & Michalek, 2012). It should also be noted that once a compressed air source has been provided, the material needed to prepare the practicum is simple and affordable, and the lab itself is very interesting and appeals to students.

Keywords – thermodynamics, energy balance, entropy balance, exergy balance, Gouy-Stodola, exergetic efficiency, vortex tube

----

1 INTRODUCTION

This paper attempts to present a program of laboratory experiences for use in courses on thermodynamics. It is designed for second year students in the Industrial Engineering degree program at the University of the Basque Country. This practical exercise is intended to provide a realistic application of the different topics covered in the thermodynamics course, such as the application of the First and Second Law to a control volume and the use of the ideal gas model. Mass, energy and entropy rate balances are evaluated in a Ranque-Hilsch vortex tube. The exergy rate balance of the process (Saidi & Allaf Yazdi, 1999; Kirmaci, 2009) is also calculated, checking the Gouy-Stodola law and obtaining the value of the exergetic efficiency of the process.

There are no major technical difficulties associated with the design of the practical laboratory session, subject to the availability of a minimally-equipped laboratory (with a compressed air supply, measuring instruments, etc.). The required investment is relatively low, as the vortex tube is used in the industrial sector and is not overly expensive. If flow meters are not available, tables provided by the manufacturer may be used.

In fact, the assembly of the equipment should not present any problems. In our case, it was decided to connect the vortex tube to the compressed air source and the manometer, using quick disconnect couplings and a semi-rigid tube. To measure temperatures, K-class flexible thermocouples were used, some of which were manufactured, while we made others ourselves using K-wire. To minimize the absorption of heat in the cold outlet flow, the thermocouple used to measure the temperature at the exit cold stream was placed near the vortex generator so the length of the cold branch tube was very short. The installation and details of the instrumentation used for the measurement of temperatures are shown in Figure 1.

Furthermore, the way in which the vortex tube works has an unusual appeal in and of itself, due to the temperatures that can be achieved and how they are reached.

2 THE MEASUREMENT

In order to achieve the proposed balances, the temperature and pressure of the air at the inlet and exit sections of the vortex tube have to be known, as well as the fraction of the input flow in each of the output streams. The speed of the air at the inlet and exit sections must be known if the kinetic energy is to be included into the energy balance. By applying the expression $\left(\frac{A \cdot V}{v} = \dot{m}\right)$, the values of the air speed and kinetic energy may be obtained, if the mass flow, the cross sectional area and the specific volume of the air are known.

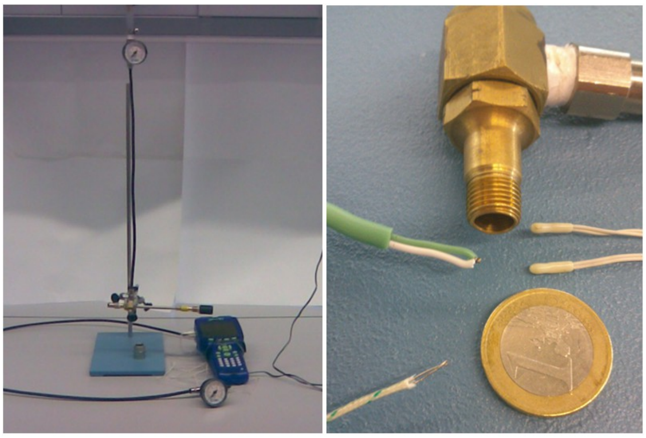

Figure 1. A general view of the laboratory equipment and details of the K-class thermocouples used

Nomenclature:

$\dot{m}$	*mass flow kg/s*	*A*	*duct cross-section (m^2)*
V	*airspeed, m/s*	*R*	*universal ideal gas constant*
T	*Temperature, K*	*cp*	*specific heat capacity at const. pres. (kJ/kg·K)*
p	*pressure, bar*	η	*exergetic efficiency (%)*
v	*specific volume, m^3/kg*	$\dot{D}$	*exergy destruction rate (kW)*
y	*cold air fraction*		
e	*energy per mass unit, kJ/kg*		
ke	*specific kinetic energy, kJ/kg*	*Subscripts*	
q	*transferred heat per mass unit, kJ/kg*	*e*	*environment*
$\dot{Q}$	*rate of heat transfer, k*	*in*	*input*
h	*specific enthalpy, kJ/kg*	*out*	*output*
s	*specific entropy, kJ/(kg·K)*	*cold*	*cold air outlet*
s^o	*absolute entropy, kJ/(kg·K)*	*hot*	*hot air outlet*
$\dot{\sigma}$	*entropy generation rate, kW/K*	*o*	*dead estate*

The material necessary to perform the proposed analysis is the tube itself and different vortex generators, which make it possible to vary the air flow and the cooling power of the tube. Manometers and temperature sensors are also needed to measure pressures and temperatures at the inlet and outlet sections. Both the inlet and exit flows can be measured by means of mass air flow meters. If these flow meters are not available, the input flow and the distribution of this flow between the cold (referred to as the fraction) and hot outflows can be calculated using the tables provided by the manufacturer, which are based on the inlet pressure and temperature variation between the inlet and outlet air streams. Using these data, air velocities and kinetic energy can also be obtained, as explained above.

In the proposed practical laboratory experience, the use and understanding by students of the thermodynamic concepts is prioritized over a highly accurate system design. Therefore, the operating model is simplified, even though a certain degree of accuracy in the data may be lost when tables are used. As will be seen later, we will check if the data recorded are appropriate, and if the calculations are correct.

3 THE VORTEX TUBE

The Raque-Hilsch vortex tube is a heat apparatus with no moving parts that divides a high-pressure fluid flow into two separate flows (hot and cold) at lower pressures. It was designed in 1930 by George J. Ranque, and improved in 1945 by Rudolf Hilsch. Its operation is based on the vortex effect created when a spin movement is induced in the pressurized inlet air by a vortex generator. Some generator models are shown in Figure 2.

Figure 2. Different vortex generators

The vortex, which may reach a rotational speed of 10^6 rpm, propagates through the tube to the hot output. A fraction of the air leaves this output, while the rest goes back into a lower pressure internal vortex to the cold output. The regulation between the hot and cold fractions will be produced in the hot output, as can be seen in Figure 3.

This phenomenon is described in many different ways in the scientific literature (Aydin & Baki, 2006; Xue, Arjomandi & Kelso, 2013a, 2013b; Patiño, Llopis, Sanchez, Torrella & Cabello, 2013), with some authors only providing a partial explanation and others seemingly contradicting one another. As in other fields of fluid dynamics, the behavior of the air inside the tube has not yet been fully explained, so that for the purposes of the practical laboratory experience, an easily understandable partial explanation in association with thermodynamic concepts is proposed. More detailed explanations can be found in the suggested references.

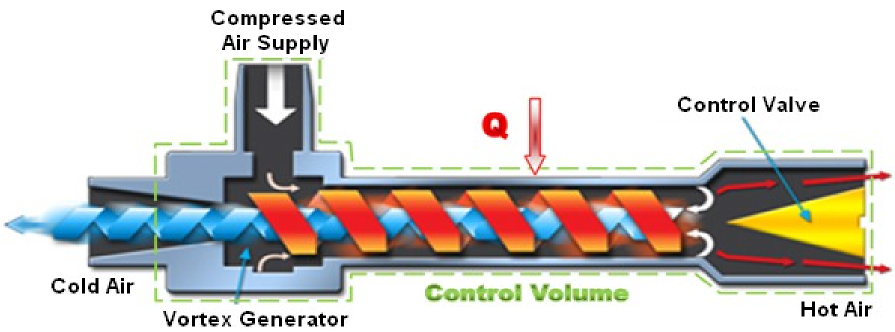

Figure 3. Vortex tube operation and control volume definition

Figure 3 shows the vortex tube and a summary of how it works, as well as the limits of the control volume in question. Two vortices can be observed; the outer one appertaining to the hot flow is at a higher pressure than the inner one, which appertains to the cold fraction. Even at steady state, there is air transfer between the two vortices. When air passes from the hot to the cold vortex, it expands (since the pressure is lower in the cold vortex) and therefore cools, lowering the temperature of the inner vortex. When air passes from the cold to the hot vortex, it is simultaneously compressed and heated, which raises the temperature of the outer vortex.

Generator model	***Air consumption (SLPM)***	***Cooling capacity (kJ/h)***
106-2-H	*57*	*104.7*
106-4-H	***113***	*268.0*
106-8-H	*226*	*422.9*
208-11-H	*311*	*674.1*
208-15-H	*425*	*950.5*
208-25-H	*708*	*1582.7*
308-35-H	*991*	*2796.9*
328-50-H	*1415*	*3165.4*
328-75-H	*2123*	*4748.1*
328-100-H	*2830*	*6330.8*

Table 1. Compressed air consumption (in standard liters per minute) and cooling capacity for different vortex generators (6.9 bar inlet pressure)

Table 1 is provided by the manufacturer and shows the inlet air consumption for a specific vortex generator at the indicated pressure. For other inlet pressure values, an approximated formula is provided to calculate the consumption based on the vortex generator type and the inlet pressure values. The value for the manufacturer's *106-4-H* generator and 6.9 bars of inlet pressure is indicated. Table 2 shows the relationship between the cold fraction of air and the temperature difference produced in each output for different inlet pressures. It is possible to estimate the cold fraction by measuring the values obtained for the temperature difference at each output and comparing them with those provided by the manufacturer in Table 2.

Cold Fraction	***10***	***20***	***30***	***40***	***50***	***60***	***70***	***80***	***90***
Pressure (bar)	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*
1.4	*35*	*34*	*33*	*31*	*28*	*24*	*20*	*15*	*9*
	4	*8*	*14*	*20*	*28*	*36*	*46*	*59*	*82*
2.8	*51*	*49*	*47*	*44*	*41*	*35*	*28*	*21*	*14*
	5	*11*	*19*	*29*	*39*	*51*	*65*	*82*	*122*
4.1	*59*	*58*	*56*	*52*	*47*	*41*	*33*	*25*	*16*
	6	*13*	*22*	*33*	*44*	*58*	*73*	*93*	*131*
5.5	*66*	*64*	*61*	*57*	*51*	*44*	*36*	*27*	*17*
	7	*14*	*24*	*35*	*48*	*63*	*79*	*101*	*138*
6.9	*71*	*68*	*66*	*61*	*55*	*48*	*39*	*29*	*18*
	8	*14*	*25*	*37*	*51*	*66*	*84*	*107*	*140*
8.3	*74*	*72*	*69*	*64*	*58*	*50*	*41*	*31*	*19*
	8	*14*	*26*	*38*	*52*	*68*	*87*	*108*	*142*
9.7	*78*	*75*	*72*	*67*	*61*	*52*	*42*	*32*	*20*
	8	*16*	*27*	*37*	*53*	*69*	*88*	*109*	*144*

Table 2. Cold fraction and temperature change between the cold and the inlet flows (in blue) and the hot and the inlet flows (in white) for various pressures

4 MASS AND ENERGY BALANCE

Once the materials and the measurements to be taken have been described, the first part of the laboratory experience can be performed. According to the law of mass conservation for the control volume depicted in Figure 2, at steady state, the total incoming and outgoing mass flow rates are equal and therefore:

$$m_{in} = m_{cold} + m_{hot} = y \cdot m_{in} + (1-y) m_{in} \tag{1}$$

The energy balance at steady state is evaluated for different values of the cold fraction, *y*. Due to the short length of the cold arm, the heat exchanged by the cold flow can be considered negligible so the control volume shown in Figure 2 is such that it allows considering just the heat exchanged by the hot flow.

The pressure and temperature of the incoming and outgoing flows are measured. As mentioned earlier, different tests have been performed by regulating the outgoing cold fraction, so the temperatures of the outgoing flows vary accordingly. The cold fraction and the outgoing flows are determined using flow meters or the tables provided by the manufacturer. At steady state, the total rate at which energy is transferred into the control volume equals the total rate at which energy is transferred out and therefore:

$$\frac{dE}{dt} = 0 = \dot{Q} + \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2}\right) - \dot{m}_{in}\left(y\left(h_{cold} + \frac{v_{cold}^2}{2}\right) + (1-y)\left(h_{cold} + \frac{v_{cold}^2}{2}\right)\right) \tag{2}$$

Although the tube is usually considered to be an adiabatic system, based on the obtained results and the didactic nature of the laboratory experience, the difference between the enthalpy and kinetic energy at the inlet and outlet section is considered to be equal to the heat exchanged. As mentioned above, in order to minimize the heat transfer in the cold arm, its length has been shortened in the control volume, so the rate of heat transfer evaluated in the energy balance, $\dot{Q}$, can be considered to be equal to the heat transfer from the hot arm. Figure 4 shows a thermal image of the vortex tube operating with a cold fraction y = 0.75.

The addition of the kinetic energy of the air to the balance has also been considormuered appropriate, due to the contribution it makes (especially in the inlet stream) and to reinforce the didactic nature of the proposed practical work.

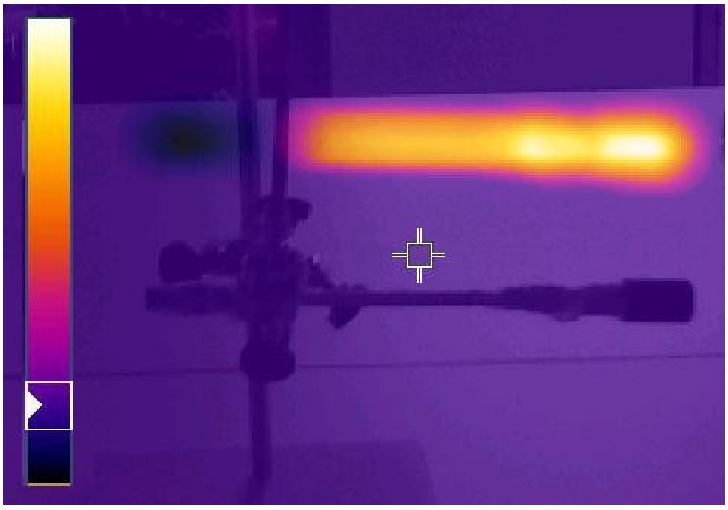

Figure 4. Thermal photography of the vortex tube operating with a cold fraction y = 0.75.
The temperature of the cold flow is -8 °C and the hot flow is 98 °C

Table 3 displays the data obtained in two tests with cold fractions y = 0.35 (test A) and y = 0.75 (test B). Table 4 exhibits the values, all expressed in kJ/kg, associated with the energy balance terms for these two tests.

	T_e (K)	T_{in} (K)	p_{in} (bar)	T_{cold} (K)	p_{cold} (bar)	T_{hot} (K)	p_{hot} (bar)	y	$\dot{m}$ (kg/s)
Test A	297	296.8	6.5	240.5	1	315.5	1	0.35	0.0022
Test B	297	296.8	6	265	1	371	1	0.75	0.002

Table 3. Definition of the tests

	h_{in} (kJ/kg)	ke_{in} (kJ/kg)	h_{cold} (kJ/kg)	ke_{cold} (kJ/kg)	h_{hot} (kJ/kg)	ke_{hot} (kJ/kg)	e_{in} (kJ/kg)	e_{out} (kJ/kg)	q (kJ/kg)
Test A	*296.98*	*3.3*	*240.5*	*0.7*	*315.5*	*8.7*	*300.30*	*295.33*	*-4.97*
Test B	*296.98*	*3.2*	*265.1*	*3.3*	*371.7*	*1.5*	*300.20*	*294.55*	*-5.65*

Table 4. Terms of the energy balance

Thermodynamics tables of the ideal gas air are used to obtain the enthalpy values in the working conditions. The ideal gas equation of state is used to calculate the specific volume of the air at each measurement point. Using these values, the air velocity and the kinetic energy are calculated for introduction into the energy balance. The use of a spreadsheet program is suggested to simplify the calculation of the results of the different tests and to make it easier to obtain results when small changes in the input data are made.

5 MAXWELL'S DEMON

By observing the air flow splitting in two flows at different temperatures, we can gain a better understanding of one of the classic mental experiments of thermodynamics: Maxwell's Demon. James Clerk Maxwell unified the theories behind electromagnetism and also worked in other fields, including thermodynamics. In his book "Theory of the Heat", he proposed the following example under the heading "Limitation of the second law of thermodynamics".

"*For we have seen that the molecules in a vessel full of air at uniform temperature are moving with velocities by no means uniform, though the mean velocity of any great number of them, arbitrarily selected, is almost exactly uniform. Now let us suppose that such a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower ones to pass from B to A. He will thus, without expenditure of work, raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics.*"

The described process could be considered similar to the one that occurs inside the vortex tube, where an air flow is separated into two separate flows, hot and cold, apparently without any work applied. It therefore seems that the entropy of the system would diminish. This approach, apparently in violation of the Second Law, is refuted in various ways, usually associated with the process of distinguishing between the two types of molecules and the entropy generated to perform the distinguishing action (Bennett, 1982). At this point, it is possible to ask about the phenomenon which occurs in the vortex tube.

The same approach can be taken in a different way. When two flows at different temperatures are mixed, there is a positive generation of entropy. This is a typical exercise to be discussed in class, reaching the conclusion that when a flow is separated into two streams at different temperatures, the entropy would decrease and the process should be impossible. The key point in this experiment is the pressure applied to the flow. There is a decrease in the pressure between the inlet and outlet flows, and this decrease in mechanical energy associated with pressure is converted into thermal energy. As a result, there is a significant amount of entropy generated during the process and the subsequent destruction of exergy, as we will see in the following paragraphs. Therefore, at this point, entropy and exergy balances will be created in order to study and understand the behavior of the system.

6 ENTROPY BALANCE

Everyday experience tells us that not every process consistent with the principle of mass and energy conservation can occur. The Second Law of thermodynamics provides a guiding principle and shows whether particular spontaneous processes occur and makes it possible to deduce their directions. Thus, the Second Law requires that entropy production (σ) results in a value that is either positive or zero. In a hypothetical process, once the entropy balance is obtained, if the value of the generated entropy is negative, this means that the process cannot happen, i.e., it is impossible.

The steady-state form of the entropy rate balance for the system of Figure 2 is applied to obtain the value of the entropy production. This value will be used to check the Gouy-Stodola relationship once the exergy balance has been reached.

The entropy rate balance at steady state takes the following form:

$$0 = \dot{m}_{in}\frac{\dot{Q}}{T_{hot}} + y \cdot \dot{m}_{in}\left(s_{in} - s_{cold}\right) + \left(1-y\right)\dot{m}_{in}\left(s_{in} - s_{hot}\right) + \dot{\sigma} \tag{3}$$

At this point, it is necessary to calculate the entropy change in the air between the inlet and outlet states. Assuming the ideal gas model for the air, this calculation has been performed based on the premise that either the specific heat at constant pressure c_p is constant or taking in account its variation with temperature as follows:

$$c_p \quad cte: \qquad s_i - s_{in} = c_p \ln\frac{T_i}{T_{in}} - R\ln\frac{p_i}{p_{in}}$$

$$c_p = c_p(T): \qquad s_i - s_{in} = s_i^o - s_{in}^o - R\ln\frac{p_i}{p_{in}} \qquad \text{for } i = cold, hot$$

These two methods are presented during the course, so their use will reinforce the work done with the ideal gas model of air.

When performing the calculations, the difference between input and output pressures can be observed. The decrease in pressure explains why the flow splits into a hot and a cold flow; this is the reason why the entropy generation obtained is positive, and there is no contradiction with the Second Law.

The values obtained for the entropy production in the two tests and the two ways to consider the specific heat c_p are reflected in Table 5. As can be observed, both results are similar. Using a program such as TERMOGRAF (http://termograf.unizar.es/), the value for s_i-s_{in} can be calculated for the air as a real gas. Small deviations will be observed between the different methods, which demonstrates how a simplified model such as the ideal gas model is valid under the proposed conditions.

The use of the T_{hot} value has been simplified. The term $\dot{Q}/T_{hot}$ is related to the entropy associated with the heat transfer. As seen in the thermography image in Figure 4, the temperature is not constant along the hot arm, even though in the calculations, the temperature of the outer surface of the hot arm has been considered uniform, and equal to the mean value of the hot stream temperature (T_{hot}).

	$\dot{Q}/T_{hot}$ **(W/K)**	$\dot{\sigma}$ **(c_p cte) (W/K)**	$\dot{\sigma}$ **(c_p(T)) (W/K)**
Test A (y = 0.35)	*–3.45E-02*	*1.14*	*1.15*
Test B (y = 0.75)	*–3.04E-02*	*1.00*	*1.01*

Table 5. Thermal entropy flow and rate of entropy generation

7 EXERGY BALANCE

In order to better understand and assess the results, a steady-state exergy rate balance is performed. This will allow quantifying the irreversibilities that occur in the compressed air as a result of its partitioning into two streams. This enables us to obtain the value of the rate of exergy destruction, $\dot{D}$, and quantify the energetic degradation of the air passing through the vortex tube.

The exergy rate balance at steady state can be written as:

$$\frac{dB}{dt} = 0 = \left(1 - \frac{T_o}{T_{hot}}\right)\dot{Q} + \dot{m}_{in}\,y\left(b_{in} - b_{cold}\right) + \dot{m}_{in}\left(1-y\right)\left(b_{in} - b_{hot}\right) - \dot{D} \tag{4}$$

where b_{in}-b_i is the difference in the specific flow exergy between the inlet state and the hot and cold outlet states, plus the kinetic energy change. Therefore:

$$b_{in} - b_i = \left(h_{in} - h_i\right) - T_o\left(s_{in} - s_i\right) + \frac{v_{in}^2 - v_i^2}{2} \tag{5}$$

When reviewing the results, high values obtained for the exergy destruction can be observed, showing a characteristic associated with the vortex tubes: their high level of irreversibility. On the other hand, the

Gouy-Stodola relation can also be verified, as the exergy destruction and the entropy generation are described by the equation

$$\dot{D} = T_o \, \dot{\sigma} \tag{6}$$

The tests results obtained are shown in Table 6. As expected, the Gouy-Stodola law is fulfilled, and the analysis that has been carried out can be considered correct.

To conclude the laboratory experience, the exergetic efficiency of the process is evaluated in two different ways: directly, comparing output exergy to the input exergy, $\eta = \frac{\dot{m}_{in} y b_{cold} + \dot{m}_{in}(1-y) b_{hot}}{\dot{m}_{in} b_{in}}$; and indirectly, through the exergy destruction and the exergy losses associated with the heat that was exchanged $\eta = 1 - \frac{\dot{Q}\left(1 - \frac{T_o}{T_{hot}}\right) + \dot{D}}{m_{in} b_{in}}$. The values obtained by both expressions should be similar in order for the experiment to be considered successful.

	Ideal gas model with c_p constant				*Ideal gas model with $c_p(T)$*		
	$\dot{D}$ *(W)*	$\dot{\sigma} \cdot T_o$ (W)	$\eta\left(\frac{b_{out}}{b_{in}}\right)$	$\eta\left(1 - \frac{\dot{Q}\left(1-\frac{T_o}{T_{hot}}\right)+\dot{D}}{m_{in} b_{in}}\right)$	$\dot{D}$ *(W)*	$\dot{\sigma} \cdot T_o$ (W)	$\eta\left(1 - \frac{\dot{Q}\left(1-\frac{T_o}{T_{hot}}\right)+\dot{D}}{m_{in} b_{in}}\right)$
Test A (y=0.35)	*0.339*	*0.339*	*5.33 %*	*5.23 %*	*0.341*	*0.341*	*4.77 %*
Test B (y=0.75)	*0.297*	*0.297*	*4.44 %*	*4.06 %*	*0.299*	*0.299*	*3.59 %*

Table 6. Check of the Gouy-Stodola relationship and the exergetic efficiency calculation

8 DEVELOPMENT OF THE WORK

The lab program can be approached in two different ways, using either a teacher-lecture approach or a student-centered approach. In our case, a problem based-learning (PBL) methodology (Felder & Silverman, 1988; Hmelo-Silver, 2004) is applied, because we consider it much more effective for the internalization of learning and skill development. This PBL methodology is widely accepted (Scott, Hadgraft & Ilic, 2003; Hsieh & Knight, 2008), and it is proposed with the aim of achieving a better understanding of the concepts behind the conservation and non-conservation of balances, as well as the different terms involved.

For each lab session, the entire class is divided into several four-student groups to encourage team work. Each group performs the experiment and writes down the data obtained. No later than fifteen days after the practicum is performed, each group is required to submit a report. The content of this report is a general description of the experiment carried out and an analysis of the results obtained through the data measured. The aim of this report is to help students improve their critical thinking and their written communication skills. There are five labs scheduled throughout the academic year, with different group members for each. The grade for the reports given for each lab accounts for 20% of the final mark for each student.

The lab session is held at a time of the year when most of the course syllabus has already been completed, so it can be used as a review and as a way to evaluate the acquired knowledge before the final evaluation takes place. Moreover, some transversal concepts are introduced, such as how a vortex tube works, the small errors made when using the ideal gas model under experimental conditions and historical references to Maxwell, his work and his era.

9 CONCLUSIONS

An attractive, easy-to-prepare and inexpensive program of laboratory experiences is proposed. During the course of the lab sessions, most of the syllabus for a course in thermodynamics is covered, including topics such as the ideal gas model, mass and energy conservation, entropy production and exergy destruction, as applied to a particular control volume, such as the vortex tube and the Gouy-Stodola relationship. In addition, the lab allows the introduction of some historical thermodynamic concepts that may be outside the scope of a regular course, such as the mention made of Maxwell’s demon and his work in the field of thermodynamics.

Worth highlighting is the proposed introduction to the concept of irreversible processes and the entropy generation associated with them through the concept of Maxwell’s demon. The theoretical impossibility of the process in the vortex tube is initially proposed, although this point is then clarified, taking into account the decrease in pressure between the inlet and outlet flows.

Within the ideal gas model, two methods are proposed to calculate the terms associated with the change in entropy that occurs in the entropy rate balance, followed by a comparison between them. The Gouy-Stodola relationship is checked, and the exergetic efficiency of the process is calculated both directly and indirectly. Any deviation would indicate an incorrect approach or errors in the calculations.

The use of a spreadsheet to perform the calculations allows students to evaluate different configurations of the vortex tube in a relatively simple manner. This can also be used to understand how the variation of the different parameters (input pressure, *y* fraction, etc.) affects the results obtained and to gain a better understanding of the subject, as well as to improve critical thinking skills.

After reviewing many reports written by students who have taken part in the lab sessions, we can highlight that the most common errors are in the evaluation of the kinetic energies, as well as in the proper approach to the exergy balance.

ACKNOWLEDGMENTS

The authors wish to acknowledge the University of the Basque Country for providing the material needed. We would also like to express our appreciation to the Laboratory for the Quality Control of Buildings of the Basque Government.

REFERENCES

Aydin, O., & Baki, M. (2006). An experimental study on the design parameters of a counterflow vortex tube. *Energy*, 31(14), 2763-2772. http://dx.doi.org/10.1016/j.energy.2005.11.017

Bennett, C.H. (1982). The thermodynamics of computation – a review. *International Journal of Theoretical Physics*, 21(12), 905-940. http://dx.doi.org/10.1007/BF02084158

Felder, R.M., & Silverman, L.K. (1988). Learning and Teaching Styles in Engineering Education. *Engr. Education*, 78(7), 674-681.

Hmelo-Silver, C.E. (2004), Problem-based Learning: What and How Do Students Learn? *Educational Psychology Review*, 16, 235-266. http://dx.doi.org/10.1023/B:EDPR.0000034022.16470.f3

Hsieh, C., & Knight, L. (2008). Problem-Based Learning for Engineering Students: An Evidence-Based Comparative Study. *The Journal of Academic Librarianship*, 34(1), 25-30. http://dx.doi.org/10.1016/j.acalib.2007.11.007

Kirmaci, V. (2009). Exergy analysis and performance of a counter flow Ranque–Hilsch vortex tube having various nozzle numbers at different inlet pressures of oxygen and air. *International Journal of Refrigeration*, 32(7), 1626-1633. http://dx.doi.org/10.1016/j.ijrefrig.2009.04.007

Lewins, J., & Bejan, A. (1999). Vortex tube optimization theory. *Energy,* 24(11), 931-943. http://dx.doi.org/10.1016/S0360-5442(99)00039-0

Liew, R., Zeegers, J.C.H., Kuerten, J.G.M., & Michalek, W.R. (2012). Maxwell's demon in the Ranque-Hilsch vortex tube. *Physical Review Letters,* 109(5), 054503. http://dx.doi.org/10.1103/PhysRevLett.109.054503

Moran, M.J., Shapiro, H.N., Boettner, D.D., & Bailey, M.B. (2012). *Principles of Engineering Thermodynamics.* Wiley

Patiño, J., Llopis, R., Sanchez, D., Torrella, E., & Cabello, R. (2013). *Incidencia de los parámetros de entrada en el funcionamiento de un tubo vortex. análisis experimental*. Proceedings of the 8th Congreso Nacional de Ingeniería Termodinámica. Burgos, Spain.

Ranque, G.J. (1934). United States Patent, n. 1,952,281

Saidi, M.H., & Allaf Yazdi, M.R. (1999). Exergy model of a vortex tube system with experimental results. *Energy*, 24(7), 625-632. http://dx.doi.org/10.1016/S0360-5442(98)00076-0

Scott, N., Hadgraft, R., & Ilic, V. (2003). Engineering Education – is Problem-based or Project-based learning the answer? *Australasian Journal of Engineering Education.* Online publication 2003-04 http://www.aaee.com.au/journal/2003/mills_treagust03.pdf

TERMOGRAF. http://termograf.unizar.es/

Xue, Y., Arjomandi, M., & Kelso, R. (2013a). The working principle of a vortex tube. *International Journal of Refrigeration,* (0). http://dx.doi.org/10.1016/j.ijrefrig.2013.04.016

Xue, Y., Arjomandi, M., & Kelso, R. (2013b). Experimental study of the thermal separation in a vortex tube. *Experimental Thermal and Fluid Science,* 46(0), 175-182. http://dx.doi.org/10.1016/j.expthermflusci.2012.12.009

Citation: Carrascal, E., & Sala, J.M. (2013). Mass, energy, entrpy and exergy rate balance in a Ranque-Hilsh vortex tube. *Journal of Technology and Science Education (JOTSE), 3(3),* 122-131. http://dx.doi.org/10.3926/jotse.86

On-line ISSN: 2013-6374 – Print ISSN: 2014-5349 – DL: B-2000-2012

AUTHORS BIOGRAPHY

Edorta Carrascal Lekunberri

He has a degree in Physics, in Electronics Engineering and another one in Maritime Navigation at the University of Basque Country. He is currently developing his PhD in Thermal Engineering and is a lecturer in the Department of Thermal Engineering at the University of Basque Country.

He is member of the research Group on Advanced Control and collaborates with the research Group ENEDI (Energetic in Edification). His current research interest is on the subject of energy in buildings and particularly on advanced control for thermal installations.

José Mª Sala

José Mª Sala is PhD in Industrial Engineering by the University of the Basque Country and M.Phil. in Theoretical Physics by the University of Sussex (U.K.)

Since 1983 he is a professor in thermodynamics and physical chemistry at the University of the Basque Country. During seven years he shared his university activities with industrial ones, being the technical manager in an engineering firm involved in developing projects and the assembly of energy installations, most of them cogeneration plants.

For many years his research activity has been devoted to energy efficiency in industrial processes, particularly with application of the exergy method of analysis and thermoeconomy. Most recently he is involved in problems related to the energy efficiency in buildings, either to the envelop or to thermal installations.

Published by OmniaScience (www.omniascience.com)

Journal of Technology and Science Education, 2013 (www.jotse.org)