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RESEARCH INTO FREON-FREE ECOLOGICAL COMPRESSED AIR COOLING AND CONDITIONING PROCESSES

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Abstract: *Documents such as the Lisbon Protocol and the EU Green Pact call for the development of environmentally friendly processes and technologies to drastically reduce greenhouse gas emissions (carbon dioxide, freons, etc.) and limit the devastating consequences of climate change. Today, most industrial refrigeration, air conditioning and personal comfort processes are carried out using equipment that uses freons (chlorofluorocarbons) as the working medium. However, the widespread use of all types of freon is questioned because of the destruction of the ozone layer in the stratosphere and the accumulation of large amounts of ultraviolet radiation on Earth, as well as the trapping of upward thermal radiation in the Earth's atmosphere, which causes the well-known greenhouse effect. This paper presents cooling and air-conditioning processes that produce artificial cold by using air as a working medium, an inexhaustible ecological resource that exists everywhere in space and time. Using compressed air as the working medium, three types of thermodynamic processes are presented theoretically and experimentally: free flow in the tube, free expansion in a centrifugal field as a proprietary solution, and expansion in a centrifugal field and energy separation/Ranque-Hilsch effect. The paper concludes by summarising the findings and making recommendations for further research.*

Keywords: *Environment and clean energy, artificial cooling, compressed air, thermodynamic cooling processes, expansion in a centrifugal field*

1. Introduction

The need to develop environmentally friendly processes and technologies, in line with the Lisbon Protocol and the EU Green Pact, is justified by the need to drastically reduce greenhouse gas emissions (carbon dioxide, freons, etc.) and limit the devastating consequences of climate change.
Today, most industrial refrigeration, air conditioning and personal comfort processes are carried out using equipment that uses Freon as a refrigerant.
However, despite the quantitative and qualitative growth that has taken place, the general use of all freons (chlorofluorocarbons) is being questioned due to the destruction of the ozone layer in the stratosphere, which allows a large amount of ultraviolet radiation to accumulate on the Earth, with harmful effects on humans, animals and plants. In addition, because of their very long persistence in the stratosphere, freon gases, together with other gases from industrial processes, contribute to the retention of upward thermal radiation in the Earth's atmosphere, causing the well-known greenhouse effect. These serious problems facing our planet are being discussed and analysed in specialised committees and decision-making forums around the world, where measures are being taken to limit the use of freons and find other substitutes.
In this respect, considering the interest of ICMET Craiova in the field of compressed air technology, this paper tries to meet the requirements of ensuring the quality and integrity of the environment, presenting theoretically thermodynamic procedures for the generation of artificial cold and initiating by experiment some applications where the refrigerant is compressed air, an environmentally friendly product for man and the environment.

2. Theoretical research

Despite the fact that air has a low coefficient of thermal conductivity (λ=0,024 W/moC, measured at 25^{o}C), its use as a working medium in thermodynamic cooling and air-conditioning processes is justified by the fact that it is an inexhaustible ecological resource that is ubiquitous in space and time.
Air compression is known to be a costly process and the higher the compression pressure, the more the resulting air overheats. This paper deals with thermodynamic processes for cooling and air conditioning using compressed air from a low pressure source (1.5 ÷ 3 bar), which produces compressed air with an outlet temperature close to the ambient temperature.
The paper presents cooling and air-conditioning processes that produce artificial cold using air as a working medium, an inexhaustible ecological resource that exists everywhere in space and time. Using compressed air as the working medium, we have theoretically and experimentally demonstrated three types of thermodynamic processes, namely: free flow in the tube, multi-jet expansion in a centrifugal field as a proprietary patented solution, and expansion in a centrifugal field with energy separation/Ranque-Hilsch effect.

2.1 Free flow in the tube

Free flow of compressed air from a tube without mechanical work, i.e. free expansion in the atmosphere, causes changes in thermodynamic parameters. The air velocity in a section of tube depends on the value of the upstream pressure, the downstream pressure, the condition of the tube surface, etc. The flow velocity in the tube increases with the pressure variation. For a given value of tube cross section, no matter how much the pressure difference between upstream and downstream increases, the flow velocity cannot increase above the speed of sound. For this maximum value reached, where the speed is equal to the speed of sound, we can say that we have reached the conditions for the so-called critical (sonic) flow.
At the free end of the tube, expansion in the atmosphere can generate air velocities up to the maximum speed of sound. For tube pressure values from a low pressure source (1.5 ÷3 bar), the temperature drop during expansion is moderate (ΔT=1÷3^{o}C).
At the same time, the release of compressed air into the atmosphere is accompanied by a loud noise that exceeds the level that the human body can tolerate.

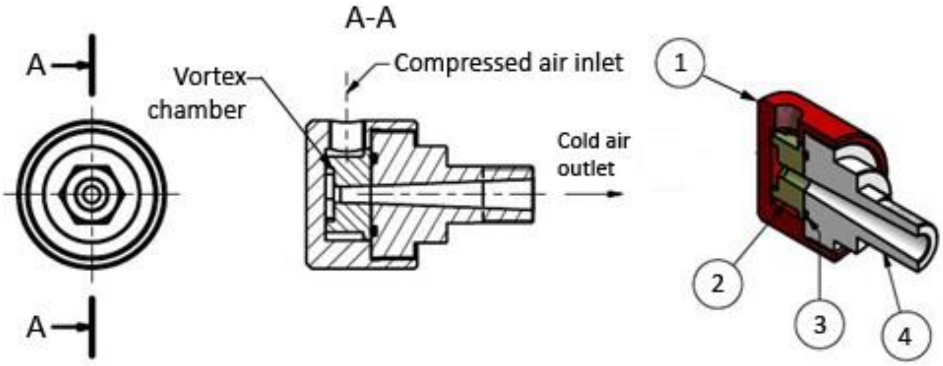
2.2 Expansion in a centrifugal field

The pneumatic cooling device for the expansion of compressed air in a centrifugal field, according to its own solution in the patent [12], shown in Figures 1a, 1b, 1c, is constructed without moving parts, i.e. from a body 1.1, a multi-jet injector 1.2, a cover 1.3 and a seal. 1.4. The multi-jet injector 1.2, shown in Figure 1b or Figure 1c, has a number of nozzle holes arranged tangentially to the diameter of the swirl chamber to divide the incoming flow of compressed air. In our approach, convergent nozzle holes of variable cross section were used to accelerate the airflow to increase the outlet velocity.
This pneumatic device has the following functions:
- Dividing the compressed air flow into multiple jets, creating a cold air spray in the swirl chamber.
- Inside the vortex chamber (axial or frontal, Fig. 1b and 1c), the noises corresponding to each jet cancel each other out, resulting in a single background noise due to centrifugation at levels acceptable to the human body.

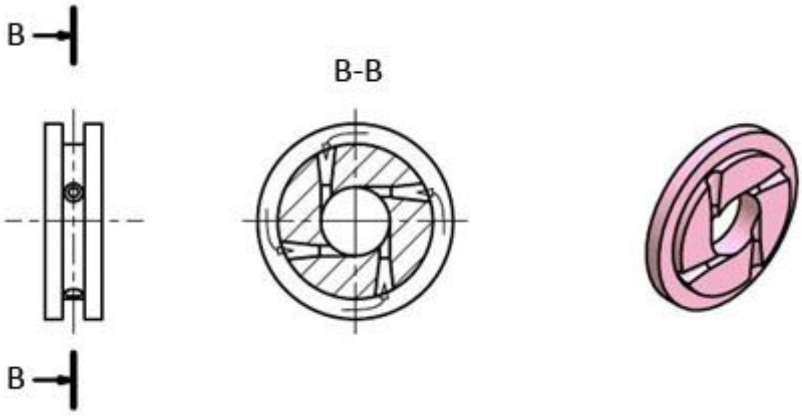
In the designed cooling device there is a series of orifices with constricted sections (nozzles) arranged tangentially to the diameter of the expansion chamber, in which irreversible thermodynamic turbulent flow phenomena occur, manifested by a sudden drop in pressure (throttling effect), increase in speed and temperature variation (Joule-Thomson effect). The reduction in gas temperature due to throttling - the positive Joule-Thomson effect - is used to achieve moderate refrigeration.
Also from a thermodynamic point of view, in the pneumatic cooling device, the temperature difference ΔT between the inlet temperature at nozzle T_1 and the outlet temperature at nozzle T_2 is:

$$\Delta T = T_2 - T_1 = \frac{w_2^2}{2c_p}, \tag{1}$$

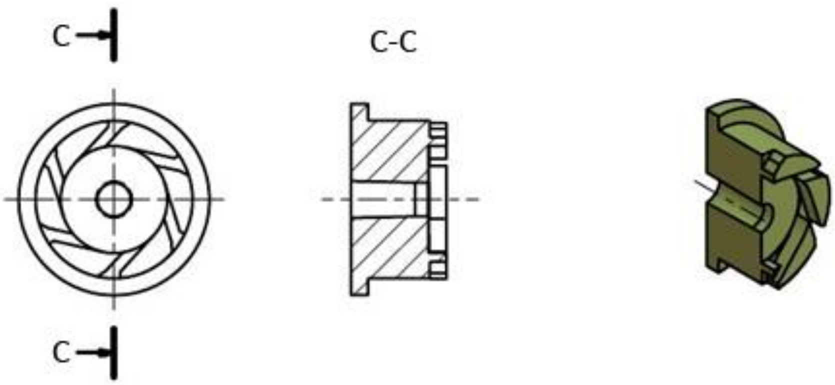
i.e. it is directly proportional to the square of the outlet velocity of the air from the nozzle w_2 and inversely proportional to the specific heat of the air at constant pressure c_p.
The cooling of the expanded air at the nozzle outlet is more significant the higher the flow velocity at the outlet. The value of the flow velocity depends on the shape (conical, truncated, Archimedean spiral, logometric spiral) and the quality of the nozzle geometry (roughness).



a. Pneumatic cooling device



b. Axial swirl chamber



c. Frontal swirl chamber

Fig. 1. Pneumatic cooling device

2.3 Expansion in a centrifugal field with energy separation/Ranque-Hilsch effect

The gas-thermodynamic phenomenon of energy separation in a vortex field of a gas by the Ranque-Hilsch effect is particularly complex and not fully understood, and is described using both known physical-mathematical relationships and a series of quantities and criteria derived from experimental research.
The general scheme of gas flow (gas thermodynamic phenomenon) in a swirl generator (turbulent flow) can be simplified as follows (Fig. 2):

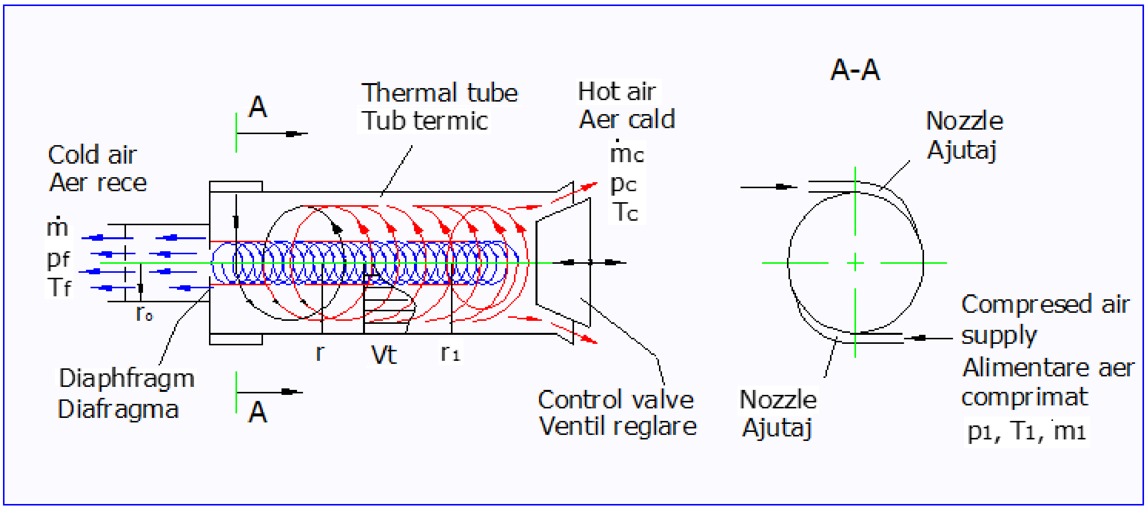


Fig. 2. Gas-dynamic phenomena in the Ranque-Hilsch tube

The compressed gas enters the generator through the nozzle, where it increases its speed due to the reduction in cross-section and is swirled due to the shape of the swirl chamber. When the gas is released into the cylindrical or truncated tube, an intense circular flow is created, characterised by the fact that the gas layers near the axis of the thermal tube cool down and are discharged through the orifice of the diaphragm, while the peripheral gas layers heat up and leave the tube through the semi-open section of the vent. By reducing the cross-sectional area of the valve, the cold gas flow through the diaphragm is increased, with a corresponding reduction in the hot gas flow. These changes are also accompanied by variations in cold and hot gas flow temperatures.
During the described process, a kinetic energy transfer and a turbulent heat exchange take place, in which elementary quantities of gas participate in the realisation of refrigeration cycles (compression-expansion) having the role of pumping energy from the central zone to the peripheral zone of the thermal tube.
In terms of flow and temperature parameters, the phenomenon can also be described as follows: the less cold air, the colder, or the more cold air, the less cold.
The flow rate of compressed gas supplied to the generator " $\dot{m}$" is the sum of the air flows leaving the generator, namely cold air "$\dot{m}_f$" and hot air " $\dot{m}_c$".

$$\dot{m} = \dot{m}_f + \dot{m}_c \;\; [kg/s] \;\; ; \;\; [m_N^3/min] \tag{2}$$

The proportion of cold air exhausted from the generator "μ"

$$\mu = \frac{\dot{m}_f}{\dot{m}} \tag{3}$$

The proportion of hot air exhausted from the generator, the difference is:

$$1 - \mu = \frac{\dot{m}_c}{\dot{m}} \tag{4}$$

The cold air proportion "μ" or the hot air proportion "1-μ" can be changed by operating the control valve.
From the thermal equilibrium equation [6], the thermodynamic temperatures characterising the cold (cooling) air flow T_f and the hot air flow T_c, at the outlet evolve according to the relationship:

$$\mu\Delta T_f = (1-\mu)\Delta T_c \quad (5)$$

where:
$\Delta T_f = T_i - T_f$, is the temperature drop of the cold flow T_f compared to the inlet temperature of the compressed air T_i.
$\Delta T_c = T_c - T_i$, is the drop in temperature of the hot flow T_c compared to the temperature of the compressed air at the inlet of the unit.
The operation of the pneumatic hot and cold air generator can also be expressed as follows: the less cold air ($\dot{m}_f \downarrow$), the colder ($T_f \uparrow$), or the more cold air ($\dot{m}_f \uparrow$), the less cold ($T_f \downarrow$).

3. Experimental research

The theoretical research presented is followed up and confirmed by experimental research in the laboratory, as follows:

a. Compressed air cooling by free flow from the tube

Figure 3a shows a schematic diagram of the circuit components and Figure 3d shows the physical components used during the experiment.

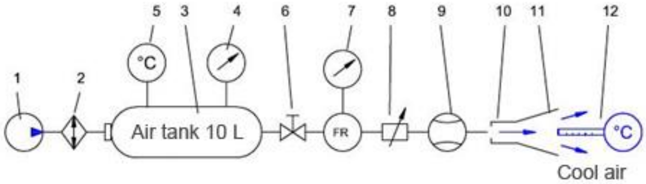


Fig. 3a. Compressed air cooling circuit by free flow from the tube

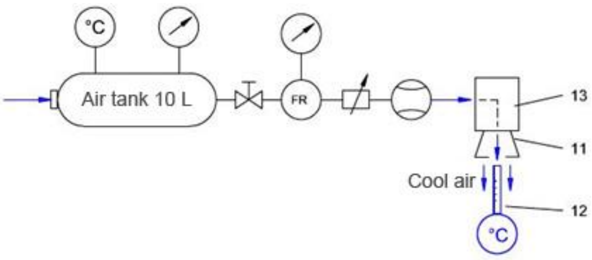


Fig. 3b. Compressed air cooling circuit by expansion in a centrifugal field

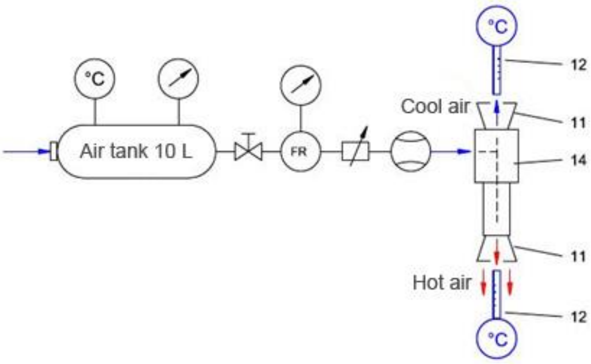


Fig. 3c. Compressed air cooling and heating circuit with vortex tube / Ranque-Hilsch

Fig. 3d. Cooling circuit components overview

Fig. 3. Experimental cooling circuits

Caption:
The equipment in the circuit represents:
1. Electric air compressor AC 1300/Makita; p_{max}=10 bar; q= 240 l/min; P=1.5 kW/230 V
2. Air-to-Air Cooler Type CSL
3. Compressed air tank V=10 litres; p_n=10 bar
4. Pressure gauge p_n=10 bar; G3/8”
5. Digital thermometer with a solid metal probe with a G1/4” thread; T=-25^o÷100^{o}C
6. Pass/no pass tap, G3/8”
7. FR pressure reducer-filter unit with pressure gauge G3/8”/SMC
8. Pneumatic throttle valve AS300/SMC; G3/8”
9. Digital calorimetric flowmeter SD6500/ifm D_n=15; p_n=15 bar; q=0.25÷75 m^3/h; Measures flow rate - pressure - temperature - total compressed air consumption
10. Compressed air tube D_n; p_n=10 bar; L=1.5 m
11. Circular diffuser
12. Digital thermometer with metal probe D3.5x120, FM10 Digi Mate; T=-50^o÷150^{o}C
13. Pneumatic cooling device by expansion in a centrifugal field DPR-ICMET Craiova
14. Cooling and Heating Vortex Tube, Model 3215 Exair Corporation

The compressed air in the circuit is supplied from a standard AC 1300/Makita source.
The pressure p_1, flow rate q_1 and temperature T_1 in the compressed air circuit and the temperature T_2 in free flow (p_2 = p_{atm}) at the end of the pipe with a nominal diameter of Dn = 6 mm were measured with the instruments shown in Figure 3a.
The working flow value was set by fine-tuning the AS 300/SMC throttle valve to the value set on the SD 6500/IFM digital flow meter.

Table 1

Cooling method	At the circuit inlet				At the circuit outlet			
	p_1 [bar]	T_1 [^{o}C]	q_1 [l/min]	v_1 [m/s]	p_2=p_{atm} [bar]	T_2 [^{o}C]	q_2=q_1 [l/min]	v_2 [m/s]
Free flow of compressed air	1.5	25.8	425	v_{11}	1	24.5	425	$v_{21}>v_{11}$
	2	25.8	425	v_{12}	1	24	425	$v_{22}>v_{12}$
	2.5	25.8	425	v_{13}	1	23.5	425	$v_{23}>v_{13}$
	3	25.8	425	v_{14}	1	23.1	425	$v_{24}>v_{14}$

By supplying the circuit with compressed air at moderate working pressures (p_1=1.5 ÷ 3 bar), an intense flow of air at a temperature slightly lower than the inlet temperature ($\Delta T=T_2-T_1$=1.3÷2.7ºC) is generated at the outlet, with high flow speeds and loud noises.

b. Compressed air cooling with a device for cooling by expansion in a centrifugal field

The structure of the circuit is shown schematically in Fig. 3b, where, in addition to the structure shown in Fig. 1a, there is the cooling device, item 11.

The compressed air cooling device shown in Fig. 1 is a new and original solution developed by a team of specialists in our institute and protected by patent RO No. 131145/2022. The originality of the solution is that all the compressed air entering the unit is converted into cooling energy by expansion and centrifugation (swirling) and exits as cold air.

Table 2

Cooling method	At the circuit inlet			At the circuit outlet		
	p_1 [bar]	T_1 [ºC]	q_1 [l/min]	$p_2=p_{atm}$ [bar]	T_2 [ºC]	$q_2=q_1$ [l/min]
Expansion and centrifugation (swirling)	1.5	26.5	425	1	23	425
	2	26.5	425	1	21	425
	2.5	26.5	425	1	17.5	425
	3	26.5	425	1	14	425

By supplying the circuit with compressed air at moderate working pressures (1.5 ÷ 3 bar), an air flow at a temperature lower than the inlet temperature ($\Delta T=T_2-T_1$=3.5÷12.5ºC) is generated at the outlet, with moderate flow speeds and noise. The process converts the entire flow of compressed air supplied to the unit into cold air ($q_1=q_2$).

c. Compressed air cooling and heating using a vortex tube/Ranque-Hilsch tube

The structure of the circuit is shown schematically in Fig. 3c where, in addition to the structure shown in Fig. 1b, we have as control element item 14 - vortex tube for cooling and heating, instead of item 13 - pneumatic cooling device.

The vortex tubes can be controlled by a dedicated valve to ensure that 20-80% of the supply flow to the compressed air device is converted to cold air and the 80-20% flow differential is simultaneously converted to hot air. With this type of Vortex Tube Model 3215, the maximum cooling capacity, i.e. the flow rate released at the cold end in conjunction with the temperature of the cooled air, is approximately 70% cold air.

The maximum cooling capacity is obtained with a proportion of 70% cold air, i.e. the product of the cold air flow and its temperature gives the best cooling capacity (P_f=190÷290 W at inlet pressures p_1=1.5 ÷ 7 bar).

Table 3

Cooling method	At the circuit inlet			At the circuit outlet				
	p_1 [bar]	T_1 [ºC]	q_1 [l/min]	$p_f=p_c=p_{atm}$ [bar]	T_2-cold [ºC]	T_3-hot [ºC]	q_2=cold [l/min]	q_3=hot [l/min]
Turbulent flow and energy separation	1.5	31	425	1	+24	+48	297	128
	2	31	425	1	+19	+54	297	128
	2.5	31	425	1	+11	+60	297	128
	3	31	425	1	+7	+67	297	128

By supplying the circuit with compressed air at moderate working pressures (1.5 ÷ 3 bar), a cold air flow is generated at the outlet with a significant temperature drop ($\Delta T=T_1-T_2=8\div24^oC$) in relation to the compressed air inlet temperature, and a hot air flow with a significant temperature rise ($\Delta T=T_3-T_1=17\div36^oC$). At the same time, the processed cold air flow rate (q_1) is approximately 2/3 and the processed hot air flow rate (q_3) is 1/3 of the supply air flow rate (q_1).

4. Interpretations and conclusions

The paper addresses a topical and globally important issue in terms of reducing emissions and finding new technologies and green agents to reduce global pollution. Thus, the use of compressed air as a working fluid in refrigeration and air conditioning systems and equipment can be a solution to replacing climate-changing freons/chlorofluorocarbons.
In industry, pneumatic energy has become the fourth largest source of energy for technological processes, despite its high cost and environmental impact.
In this context, this paper deals theoretically and experimentally with the phenomenon of obtaining moderate refrigeration from compressed air by thermodynamic methods.
It has been shown both theoretically and experimentally that the method of free flow of compressed air from the tube achieves an insignificant reduction in outlet temperature and noise.
The method of compressed air expansion in a pneumatic device (patented solution) by dividing the incoming compressed air flow into a number of jets and centrifuging them in a swirl chamber is an attractive solution for air conditioning in terms of moderate temperature drop ($\Delta T=3.5\div12.5^oC$) in relation to the ambient temperature.
The method of expansion in a centrifugal field and energy separation in the Ranque-Hilsch tube, at moderate compressed air supply pressures (1.5 ÷ 3 bar), produces cold and very cold air flows with temperature differences $\Delta T=8\div24^oC$ and, at the same time, secondary hot air flows with $\Delta T=17\div36^oC$.
To summarise:
- The method of compressed air free flow is of no interest either from an energy point of view or in terms of the noise pollution it produces.
- The method of multi-jet expansion in a centrifugal field of compressed air, converting the entire flow of compressed air into moderately cold air, is of interest for environmentally friendly air conditioning.
- The method of expansion in a centrifugal field and energy separation into hot and cold is already being used in industrial and laboratory applications.

The further development of thermodynamic methods, multi-jet expansion and expansion and energy separation devices may also be of interest to the scientific and technical community and, not least, to applicants.

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