

## **Exergetic Analyse for the Cooling Systems with R-407 Refrigerant for Application in Nuclear Plants**

SORIN GHERGHINESCU

National Institute of R&D for Cryogenics and Isotopic Technologies (ICIT)  
code 240050 - Rm. Valcea, Uzinei 4, CP7 Riureni, Valcea, ROMANIA,  
phone:0040 250 736979, fax:0040 250 732746,  
e-mail: sorin@.icsi.ro ; sorin70g@yahoo.com

*Abstract:* The experimental Pilot plant for tritium and deuterium separation, part of National Research and Development Institute for Cryogenics and Isotopic Technologies - ICSI Rm.Valcea, as principal target have to establish the technology of the water-hydrogen catalyzed isotopic exchange and cryogenic distillation for mixtures of hydrogen and his isotopes diatomic species.

The main target of the experimental pilot plant is to establish the detritiation technology of CANDU reactor moderator and to certify the equipments specific for cryogenic domain and tritiated mediums.

The most important part of the experimental Pilot Plant for Tritium and Deuterium Separation is module 300(cryogenic distillation of hydrogen/deuterium/tritium mixture). The principal goals on to that module are:

- a) to insure and maintain the proper temperature for hydrogen condensation in the head of the distillation column,
- b) to elaborate the high efficiency contact elements on hydrogen isotopes separation.

In real conditions the processes of refrigeration cycles, are accompanied by internal and external irreversibility, which have the effect of consumption need of work, higher than ideal for cold cycle, characterized by the absence of irreversibility. The most representative irreversibility of the refrigeration cycles are:

- External irreversibility due to heat transfer at finite temperature differences;
- Internal irreversibility due to friction, turbulence, mixing, etc..

As the coolant temperature is closer to ambient temperature, the cooling efficiency is higher. Another disadvantage of using refrigeration efficiency in qualitative analysis of refrigeration cycles is that not take account of irreversibility that occurs in refrigeration processes. Reasons presented below, will be considered the irreversibility and losses from them and will introduce the concept of exergetic efficiency, refrigeration cycle performance indicator that takes into account both the environmental temperature cooled, and the environment, and losses due to thermal processes manifested by irreversibility of component refrigeration cycles. Variable refrigerant flow multi systems are a very cost effective alternative to chiller, both in terms of installed cost, and running costs.

*Keywords:* Refrigeration efficiency, irreversibility, R407 refrigerant, nuclear plants

### **1. INTRODUCTION**

The Montreal Protocol (1987) is a landmark in environmental policy making. It was an international treaty designed on the basis of scientific evidence, to prevent rather

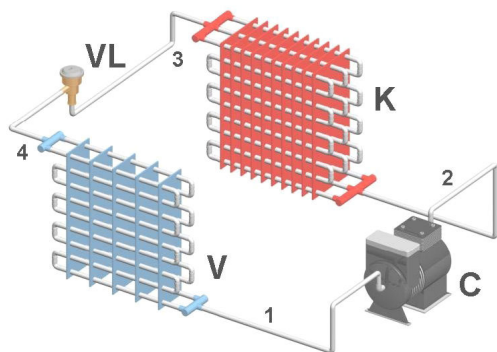
than cure the problem. The Montreal Protocol (1990) initially dealt with the phase out of FC's, by the year 2000 including R12, which has an Ozone Depletion Potential

index of 1.0. However, subsequent meetings and agreements within the EEC, the phase out date was brought forward to 1995.

Further meetings between the Member Parties of the Protocol and the EEC recognised the burden placed on industry as a whole by the rapid removal of CFC's, and allowed HCFC's as transitional substances. These were added to a list of controlled substances, although refrigerant R22 has an Ozone Depletion Potential index of 0.055, which is 5% of that of R12.

HFC production will increase as HCFC's are phased out. Whilst refrigerant HFC407C (R407C) is at 03/99 some 20% more expensive than HCFC22 (R22), the price of R22 is progressively increasing.

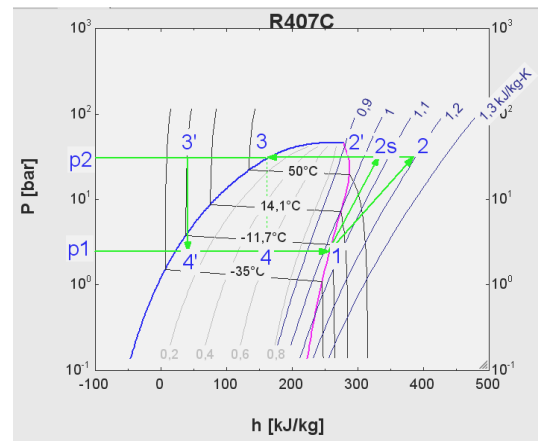
Due to the reduced production of R22, there will no longer be the economies of scale, resulting in a high priced refrigerant, against R407C whereby the economy of scale in production will become effective.



**Figure 1**

Working principle of refrigeration systems

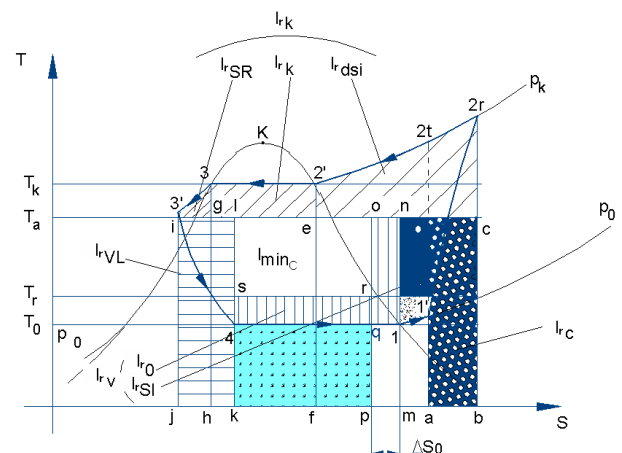
- VL – Throttle valve
- V- Evaporator
- K – Condenser
- C – Compressor



**Figure 2**

The real process in p-h diagram, for R407 refrigerant

## 2. SYSTEM ANALYSIS



**Figure 3**

The irreversibility of refrigeration cycle

Cooling efficiency, provides comprehensive information on the performance level of the cycle, but is a parameter that does not take into account the cold quality obtained.

In Figure3 is represented in the T-S diagram, a real refrigeration cycle with the subcooled in condenser and overheating in vaporizer, which allows the study of the major irreversibility of the refrigeration cycles.

For the calculation of all losses due to irreversibility and generally denoted by  $I_r$ ,

is used Guy-Stodola theorem, which in mathematical terms can be written as:

$$Ir = T_a \cdot \Delta_{s\_sys} \quad (1)$$

where  $T_a$  is ambient temperature and  $\Delta_{s\_sys}$  entropy change in thermal system that includes the entropy change with the environment,  $\Delta_{s\_hs}$  entropy of heat sources and  $\Delta_{s\_ra}$  entropy of refrigerant agent:

$$\Delta_{s\_sys} = \Delta_{s\_hs} + \Delta_{s\_ra} \quad (2)$$

Ideal compression process is represented by the diagram in Figure 3 by adiabatic transformation 1'-2t characterized by a constant entropy and the real process is represented by polytropic transformation 1'-2r characterized by increasing entropy due to internal irreversibility. Irreversibility of this process are internal, and in the absence of thermal interactions with the environment.

Losses due to irreversibility of compressor process can be calculated by the relationship:

$$Ir_c = T_a \cdot \Delta_{s\_ra} = T_a \cdot (s_{2r} - s_{1'}) \quad (3)$$

area a,b,c,d

Real process of condensation, represented on the chart by isobaric transformation 2r-2'-3-3' (Figure 3), is characterized by external irreversibility due to heat transfer at finite temperature differences. Condensation process can be split into three subprocesses: low overheating 2r-2', 2'-3 condensation and subcooling process 3-3'. For each stage of the condenser heat transfer, we can write Guy-Stodola equation for determining the losses due to irreversibility.

Losses due to irreversibility of the low overheating process are calculated by:

$$Ir_{loh} = T_a \cdot (\Delta_{s\_HSloh} + \Delta_{s\_ra}) = q_{loh} + T_a \cdot (s_{2'} - s_{2r}) \quad (4)$$

area 2r, 2', e, c

where  $\Delta_{s\_HSloh}$  is the change in entropy of hot source after overheating process, because it (the environment) absorbed specific heat of low overheating.

Losses due to irreversibility of the condensation process are calculated by:

$$Ir_c = T_a \cdot (\Delta_{s\_HSc} + \Delta_{s\_ra}) = q_c + T_a \cdot (s_3 - s_{2'}) \quad (5)$$

area 2', 3, g, e

where  $\Delta_{s\_HSc}$  is the change in entropy of hot source after condensing process, because it (the environment) absorbed specific heat of condensation process.

Losses due to irreversibility of the subcooling process

$$Ir_{SC} = T_a \cdot (\Delta_{s\_HSsc} + \Delta_{s\_ra}) = q_{sc} + T_a \cdot (s_3 - s_{2'}) \quad (6)$$

area 3, 3', i, g

where  $\Delta_{s\_HSsc}$  is the change in entropy of hot source after subcooling process, because it (the environment) absorbed specific heat of subcooling process.

Losses due to irreversibility of the throttling adiabatic process

$$Ir_{tv} = T_a \cdot \Delta_{s\_ra} = T_a \cdot (s_4 - s_{3'}) \quad (7)$$

area l, i, j, k

Real process of vaporization 4-1-1' (Figure 3) is accompanied by irreversibility due to heat transferred to finite temperature differences. Vaporization process can be divided into two phases, the vaporization 4-1 and overheating 1-1'.

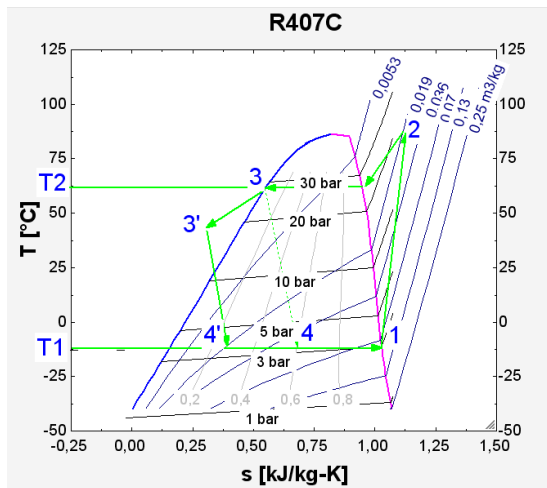
$$Ir_o = T_a \cdot (\Delta_{s\_ra} - \Delta_{s\_sc0}) = T_a \cdot \Delta_{s\_o} \quad (8)$$

area m,n,o,p

$$I_{r_{oh}} = T_a \cdot (\Delta_{s_{ra}} + \Delta_{s_{SCoh}}) \quad (9)$$

$$= T_a \cdot (s_{1'} - s_1) - q_{oh}$$

area n,d,1,1' (Figure 3)

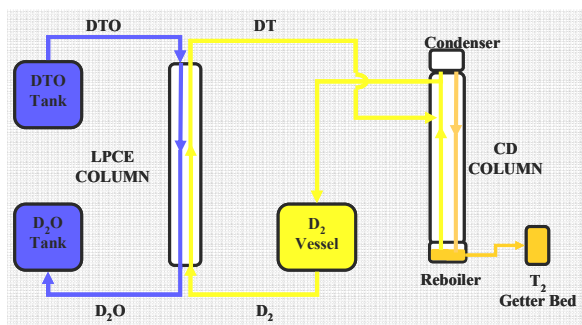


**Figure 4**

The real process in T-s diagram, for R407 refrigerant

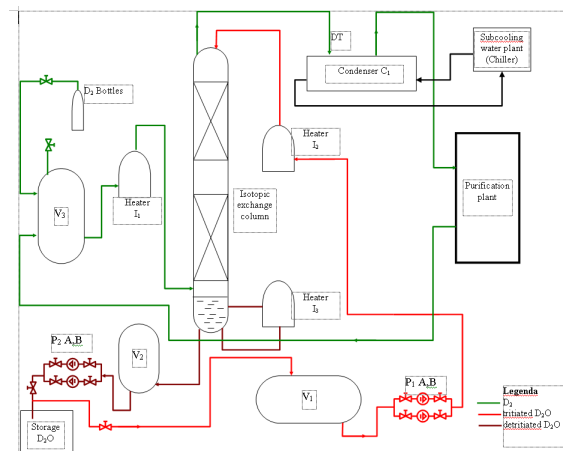
### 3. APPLICATION

The experimental Pilot Plant for Tritium and Deuterium Separation, part of National Research and Development Institute for Cryogenics and Isotopic Technologies - ICSI Rm. Valcea, as principal target have to establish the technology of the water-hydrogen catalyzed isotopic exchange and cryogenic distillation for mixtures of hydrogen and his isotopes diatomic species.



**Figure 5**

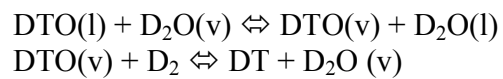
The flow diagram of a combined LPCE-CD heavy water detritiation process



**Figure 6**

The Chiller system in isotopic exchange process

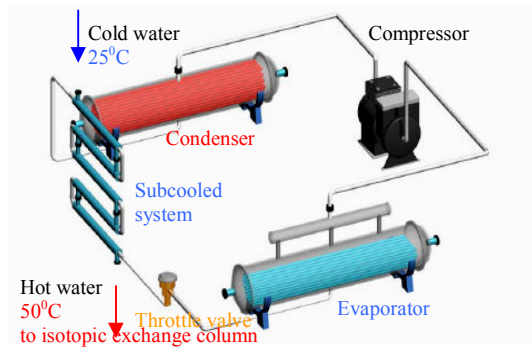
In LPCE module the tritium is transferred of water in deuterium flow by catalytic exchange in liquid phase:



- l – Liquid phase
- v – Vapour phase

Transfer process occurs on hydrophobic catalytic fillers that allow direct contact between water and deuterium gas in liquid form on the catalyst surface.

Deuterium, enriched in heavy isotopes, leaving at the top of LPCE column and enter in C1 condenser, where is cooled and condensed the water vapor, cooling circulation achieved by countercurrent flow with subcooled water at temperature 4 - 6°C. Subcooled water system consists of a fully automated Chiller, cooling water being mixed with antifreeze. Of C1 condenser, deuterium is sent to plant 200 for advanced drying.



**Figure 7**  
Use of subcooling system to coupled at isotopic exchange column

**Table 2.1.** Comparative analysis of cycles with and without subcooled

without subcooled	with subcooled	Comments
specific cooling power $q_0 = h_1 - h_4$	specific cooling power $q_0 = h_1 - h_4' > q_0$	advantage
mass flow of the plant $\dot{m} = \frac{\dot{Q}_0}{q_0}$	mass flow of the plant $\dot{m}' = \frac{\dot{Q}_0}{q_0'} < \dot{m}$	advantage
compression work $l = h_2 - h_1$	compression work $l' = h_2 - h_1 = l$	
power needed to compression $P = \dot{m} \cdot l$	power needed to compression $P' = \dot{m}' \cdot l' < P$	advantage
specific power of condenser $q_k = h_2 - h_3$	specific power of condenser $q'_k = h_2 - h_3 = q_k$	
	specific heat of subcooling $q'_{sc} = h_3 - h_3'$	
thermal load of condenser $\dot{Q}_k = \dot{m} \cdot q_k$ $= \dot{Q}_0 + P$	thermal load of condenser and subcooling $\dot{Q}_k + \dot{Q}_{sc} = \dot{m} \cdot (q_k + q_{sc})$ $= \dot{Q}_0 + P < \dot{Q}_k$	advantage
cooling efficiency $\varepsilon = \frac{\dot{Q}_0}{P}$	cooling efficiency $\varepsilon' = \frac{\dot{Q}_0}{P'} > \varepsilon$	advantage
exergetic efficiency $\eta_{ex} = \varepsilon \cdot \left( \frac{T_a}{T_r} - 1 \right)$	exergetic efficiency $\eta'_{ex} = \varepsilon' \cdot \left( \frac{T_a}{T_r} - 1 \right)$ $> \eta_{ex}$	advantage

#### 4. CONCLUSION

A theoretical comparison, of refrigerant R407C and R22 in the cooling mode is given in Table 3.1

**Table 3.1**

Refrigerant	R407C	R22
Evaporator Temperature °C	1	1
Condenser Temperature °C	38	38
Compress Efficiency Isentropic %	74	74
Evaporator Outlet	4	4
Cooling Power kW	14.5	14.5
Calculated data		
Condenser Pressure Bar	18	17.5
Evaporator Pressure Bar	3.5	3.1
C.O.P.	3.536	3.536
Compressor Power kW	4.1	4.1
Volumetric Flow into Compressor m3/hr	11.5	11.5

In the heating/cooling mode (Table 3.1) the refrigerants have similar performance properties, and therefore R407C in terms of thermodynamic performance properties is an acceptable alternative to R22.

The most important technical difference between R407C and the hydrochlorofluorocarbon R22, is that R22 has chlorine as part of its chemical structure, which now makes it totally unacceptable as a refrigerant for the future.

Of the chiller refrigeration cycle analysis reveals that is possible to increase the exergetic efficiency by recovery the subcooling heat and reinsertion to circuit of isotopic exchange column (Heater II, fig. 6).

The Chiller system is equipped to R407 refrigerant. Whilst refrigerant R22, an HCFC, is not so environmentally aggressive as a CFC refrigerant, it is being phased-out of production, and will eventually no longer be a viable proposition as a first choice refrigerant for new installations.

In the heating mode both refrigerants have similar performance properties, and therefore R407C in terms of thermodynamic performance properties is an acceptable alternative to R22. The most important

technical difference between R407C and the hydrochloroflourocarbon R22, is that R22 has chlorine as part of its chemical structure, which now makes it totally unacceptable as a refrigerant for the future.

Can observe that in refrigeration systems, is always advantageous to achieve subcooling and overheating of the system.

In this case increase the exergetic efficiency, cooling efficiency, and specific cooling power.

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