



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN - ST Division

ST-Note-2003-019

4 April 2003

USE OF FLUOROCARBONS IN THE COOLING OF LHC EXPERIMENTS

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Abstract

Perfluorochemicals sold by 3M under the trade name 3M Fluorinert Electronic Liquids have been used for many years as heat transfer media in a variety of industries. The suitability of these liquids for the cooling of LHC experiment originates from their high dielectric strength as well as from their chemical stability under ionizing radiation. The Fluorinerts are clear, colorless, non-flammable with low toxicity and low corrosiveness. Additionally, they offer low global warming potential – GWP – and zero ozone-depletion potential – ODP.

Some examples of fluorinert application in the cooling of LHC experiments will be presented : (a) the ATLAS Inner detector C3F8 evaporative cooling system (b) the ATLAS TRF C6F14 monophasic cooling system and (c) the ALICE SPD “active heat pipe” C4F10 evaporative cooling system. A brief comparison of evaporative and monophasic cooling systems will be outlined.

Presented at the 6th ST Workshop
Thoiry, France, April 1 – April 3, 2003

1 GENERALITIES ON THE USE OF FLUOROCARBONS

Fluorocarbons are a family of compounds containing carbon and fluorine only. They are particularly suited for the cooling of High Energy Physics electronics because of their high dielectric strength and non-flammability. Other advantages include low degree of toxicity, zero ozone depletion potential and a good degree of compatibility with most metals and plastics. Main shortcomings are high cost (60~200CHF/Kg), high global warming potential and long atmospheric lifetime.

In some applications within the cooling of LHC detectors, fluorocarbons will be submitted to important radiation levels. In spite of their good stability under ionizing radiation, care must be taken to ensure a high degree of fluorocarbon purity, as irradiation tests carried out at CERN show that under ionizing radiation and in the presence of H donor impurities (such as water), fluorocarbon molecules may break down to form HF acid [1]. The extension of this reaction is not well known, yet several actions can be envisaged to prevent this phenomenon:

- Demanding a high degree of purity from the supplier. Since saturated fluorocarbons $C_nF_{(2n+2)}$, are produced from alkane precursors, testing for residual H contamination is desirable (by means of the Fourier Transform infrared signature of C-H bonds).
- Rigorous initial cleaning of the installation, including supply and return lines
- Rigorous leak tightness check of the installation. Even though the pressure at every point in the circuit is most often above atmospheric, in case of a leak, some back-diffusion of air into the system may also occur.
- Fluorocarbon should not be in contact with any material likely to release pollutants into the system.
- Continuous on-line removal of water and oxygen, such as oxysorb® and alumina filters. The former guarantees H_2O and O_2 down to ppb magnitude. The latter ensures that all traces of acid are totally removed. On-line measure of water and oxygen content at ppb level is difficult and expensive so it is rarely included in the systems. Instead, periodic collection of samples should be analyzed off-line.

2 COOLING BY LIQUID CONVECTION OF FLUOROCARBONS

2.1 Heat transfer and Hydraulic Performance of fluorocarbons

The Dittus-Boelter correlation for convection heat transfer from / to a turbulent flow in a circular pipe is:

$$Nu_D = 0.023 Re_D^{0.8} Pr^{0.4} \quad (a)$$

where :

Re_D is the Reynolds number, Pr is the Prandtl number and Nu_D is the Nusselt number. Grouping the relevant physical properties, (a) yields for the heat transfer coefficient h :

$$h = 0.023 \times (K^{0.6} \mu^{-0.4} \rho^{0.8} Cp^{0.4}) \times (D^{-0.2} U^{0.8}) \quad (b)$$

where

K is the thermal conductivity, μ is the dynamic viscosity, ρ is the density and Cp the specific heat and D is the duct hydraulic diameter and U the flow speed

The variables grouped in the first bracket are liquid dependent properties whereas the second bracket characterizes the system.

A similar reasoning can be applied to the hydraulic performance:

$$\Delta P = \frac{0.092}{\text{Re}^{0.2}} \cdot \rho \cdot U^2 \cdot \frac{L}{D} \quad (\text{c})$$

$$\Delta P = (0.092 \cdot \rho \cdot \nu^{0.2}) \cdot U^{1.8} \cdot L \cdot \frac{1}{D^{0.5}} \quad (\text{d})$$

where

ΔP is the pressure drop, ρ is the density, ν is the kinematic viscosity and L is the duct length. The term between brackets depends exclusively on the liquid properties.

The comparative values of heat transfer and hydraulic groups of variables grouped in (b) and (d) are shown in table 1 for water, two fluorocarbons- C_6F_{14} and C_8F_{18} - and two other commonly used heat transfer liquids.

Table 1

	At 10°C	$\text{K}^{0.6} \cdot \mu^{-0.4} \cdot \rho^{0.8} \cdot \text{Cp}^{0.4}$	$0.092 \cdot \rho \cdot \nu^{0.2}$	At -10°C	$\text{K}^{0.6} \cdot \mu^{-0.4} \cdot \rho^{0.8} \cdot \text{Cp}^{0.4}$	$0.092 \cdot \rho \cdot \nu^{0.2}$	- HEAT
H_2O		72588	6.1				
C_6F_{14}		19609	8.6		17691	9.4	
C_8F_{18}		15905	10.42		13546	11.7	
mix 50/50 water / methanol		30200	6.8		28002	7.6	
SYLTHERM XLT		14579	5.7		12883	6.23	

TRANSFER and HYDRAULIC PERFORMANCE OF SEVERAL COOLING LIQUIDS

It can be seen that water is by far the best coolant in terms of heat transfer and hydraulic performance. Heat transfer performance of fluorocarbons is not particularly high and their hydraulic performance is in fact quite poor. In other words, when compared with an equal flow rate of water, fluorocarbons introduce a higher pressure drop (40~70% higher) and in order to achieve the same heat transfer coefficient, the flow rate has to be increased 4~5 times, increasing the pressure drop even further. This poor performance illustrates that the only reason for using fluorocarbons is their high dielectric strength and non-flammability.

2.2 Example of a liquid cooling system at CERN

The **ATLAS TRT** is a combined straw tracker and transition radiation detector to be maintained at room temperature whilst dissipating 70kW. The chosen fluorocarbon is C_6F_{14} [2], pumped into the detector at 14°C and returning to the cooling plant at 20°C. The pressure drop inside the detector is expected to be several bars, thus ruling out the use of the so-called “leakless” (sub-atmospheric operation) mode. Nevertheless, once the system is working in steady state operation, the liquid level in a reservoir will be permanently monitored for hints of any eventual leakage. Plant components such as heat exchangers, pumps, flow-meters etc, require careful selection given the liquid distinct properties vis-à-vis water or other common industrial fluids.

3 COOLING BY EVAPORATION OF FLUOROCARBONS

3.1 Advantages of evaporation vis-à-vis liquid cooling

The poor heat transfer properties of fluorocarbons can be surmounted if evaporation is considered instead of liquid convection. Several arguments can be put forward in favour of evaporation:

- Enhancement of heat transfer: the heat transfer coefficient changes progressively as the refrigerant evaporates along a duct (see Figure 1). The vapour fraction increases and the agitation thereby caused enhances the heat transfer coefficient. When the refrigerant is nearly

all vaporized, the coefficient drops off to the magnitude applicable to vapour transferring heat by forced convection.

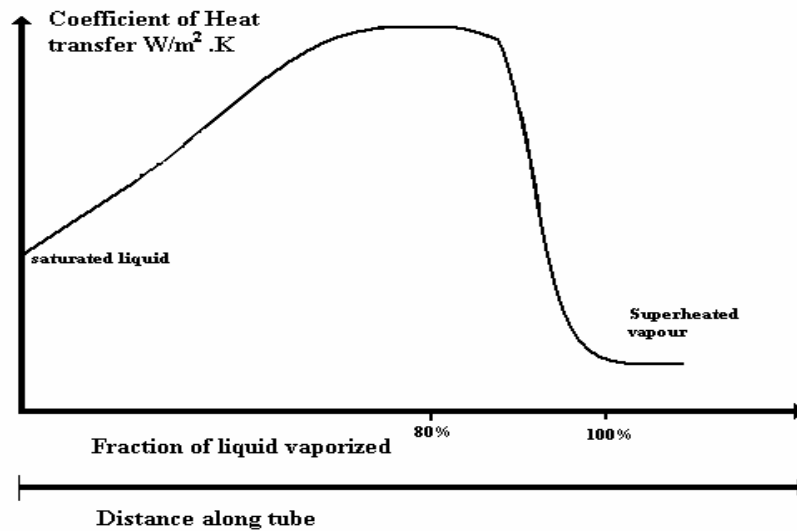


Figure 1 – evolution of heat transfer coefficient along the evaporation duct

- b) Smaller pipe diameters. The latent heat of evaporation being much higher than the sensible heat, flow rates can be reduced substantially if use is made of the former instead of the latter. Example: cooling 1 kW with C_3F_8 at $-30^\circ C$ can be achieved by:
- 1) evaporating **9.62 g/s** of liquid C_3F_8
 - or...
 - 2) increasing 1 K the temperature of a **1000 g/s** flow of liquid C_3F_8
- Smaller pipe diameters mean less mass- a frequent requirement in HEP detector cooling.
- c) Lesser temperature gradient along the evaporation duct: the heat transferred to the liquid is used for phase change and not to increase its temperature, so the temperature gradient along the stave is very small. Temperature uniformity is a common requirement for HEP detector cooling
- d) Pipe wall thickness can be reduced. The fluorocarbons family span over a wide range of saturation curves, hence evaporation at moderated pressure is always possible at any given temperature, if the right product is chosen (example: for high temperature applications C_4F_{10} is the common choice: $P_{SAT}=1.9\text{bar}$ at $15^\circ C$ whereas for low temperatures, C_3F_8 is preferred: $P_{SAT}=1.7\text{bar}$ at $-25^\circ C$). With such relatively low pressures, thinner pipes may be used.
- e) Possibility to have parallel channels at different temperatures. Evaporation temperature can be easily set individually to each circuit by means of back-pressure regulators downstream of the evaporation duct. Such control is impossible in a parallel liquid cooling systems with a single liquid supply temperature...
- f) Little pipe insulation required: insulation is only needed downstream of the expansion device, which usually is very close to the detector.

3.2 Examples of evaporative systems at CERN

3.2.1 *The ALICE Silicon Pixel Detector is the innermost detector of the ALICE experiment. Sixty cooling ducts of extremely thin wall thickness ($\sim 40\mu m$) cool this small cylinder shaped detector. The total heat to be removed is currently estimated at 2400W. In order to secure a*

safe temperature margin above dew point, the cooling ducts are to be kept at a temperature never lesser than 15 °C at all times. Being the first detector encountered by particles issuing from the collision point, material has to be kept to a bare minimum. As a consequence of the extremely thin cooling ducts, the coolant pressure must also be moderated and the mass of coolant within the detector must be as low as possible. Moreover, temperature uniformity along the evaporation duct is also a desirable feature. C₄F₁₀ has been selected for this application for its moderated evaporation pressure at 15 °C.

3.2.2 *The ATLAS Inner tracker dissipates a total of 60kW and needs to be maintained -25 °C. The cooling is conveyed by 400 cooling circuits and the detector volume is surrounded by an evaporative thermal screen. Here again, material has to be kept to a bare minimum and temperature gradient along the evaporation ducts has to be as small as possible. C₃F₈ was the selected fluorocarbon for this application, evaporating at -25 °C with a pressure of 1.7bar*

4 CONCLUSIONS

Apprehension that leaks may develop and cause substantial damage, has led to the abandonment of water as a coolant in many LHC detectors and the adoption of dielectric liquids. Moreover, the high radiation levels inside some detectors impose further constraints in the choice of coolant. Fluorocarbons are the only dielectric coolants having a stable enough molecule to withstand such high radiation environment.

Nevertheless, fluorocarbons have relatively weak heat-transfer and hydraulic performances when used in liquid convection. Evaporation is a much more attractive solution given the exceptional thermodynamic properties of fluorocarbons when undergoing a phase change.

There are currently several fluorocarbon cooling systems, both liquid and evaporative, envisaged for all 4 LHC experiments.

REFERENCES

- [1] Hallewell, G. *et al.*, *Fluorocarbon evaporative cooling developments for the ATLAS Pixel and Semiconductor Tracking detectors*, ATL-INDET-99-016
- [2] Godlewski, J. *et al.*, "A monophasic cooling system for detector front-end electronics - The example of the ATLAS TRT Detector", ATL-IT-MM-0003, May 1999

APPENDIX: LIST OF STYLES (**APPENDIX HEADING STYLE**)

We can accept contributions prepared on a Macintosh or PC using Microsoft Word (version 97 or later). Figures should be included in the text where possible, but the graphic files for each of the individual figures should also be provided. We can handle PICT, TIFF, Postscript and Encapsulated Postscript files. (**first paragraph style**)

The present instructions were prepared using the Word template which is provided for preparing your contribution. A model contribution is also provided. Table A.1.1 specifies which styles should be used for each part of your contribution. (**paragraph style**)

Table A.1.1 (table number style)
List of styles to be used in preparing contributions in Word (**table caption style**)

Part of contribution	Style
Title of the contribution	title
Space between header and references	space before doc#
CERN reference and date	ref. doc & date
Space between references and title	space before title
Abstract title	title
Names of the authors	authors
Text of abstract	abstract text
Section heading numbered	Heading 1
Subsection heading numbered	Heading 2
Sub-subsection heading numbered	Heading 3
Section heading unnumbered	Section
Text following section, subsection or sub-subsection heading	first paragraph
Other text	paragraph
List (to be used for itemized list) level 1	item list (-)
List (to be used for itemized list) level 2	item list (.)
List (to be used for itemized list) numbered	item list a)
Figure number and caption	figure caption
Table number	table number
Table caption	table caption
Text in table	table text
List of references	references
Appendix heading	appendix heading

FORMULAE (**SECTION STYLE**)

Equations may be written using the equation editor that is provided in Word: Insert → Object → Microsoft Equation 3.0. (**first paragraph style**)