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Cooling of the Straws in the ATLAS TRT

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Abstract

The straws in the TRT will generate heat that has to be removed from the detector volume to ensure stable conditions. In this report we define the boundary conditions from mechanical and physics requirements taking the barrel TRT as example. Calculations on the heat generated in the straws and its function of radius, total heat generation and the temperature distribution in the detector volume with and without active cooling are performed. Different cooling schemes are proposed and the required gas flows for these schemes are calculated. The size of the services for two different cooling schemes is discussed.

1 Distribution of Power Dissipation

The expected rate for the inner (r = 0.63 m) and outer (r = 1.07 m) straw layer is $2\text{x}1.5\ \text{x}10^7\ \text{s}^{-1}$ and $2\text{x}3.8\text{x}10^6\ \text{s}^{-1}$ respectively [1]. The power dissipation in the 1.6 m long barrel straws follows from:

$$W = Gain \times N \times Rate \times V \times q \qquad (1)$$

where N is the *mean* number of ions produced per hit in the straw, V is the anode wire potential and q is the deposited electron charge. With Gain = $4\text{x}10^4$, N = 65, V = 1800 V and Rate = $3.0\text{x}10^7\ \text{s}^{-1}$ (inner layer) we obtain W = 22 mW. Assuming that the rate per straw varies with radius as

$$Rate \propto \frac{1}{r^a}, \qquad (2)$$

the rates for the inner and outer layer above give $a \approx 2.51$. This gives a heat distribution as shown in figure 1 and the total power dissipation in the barrel is 574 W.

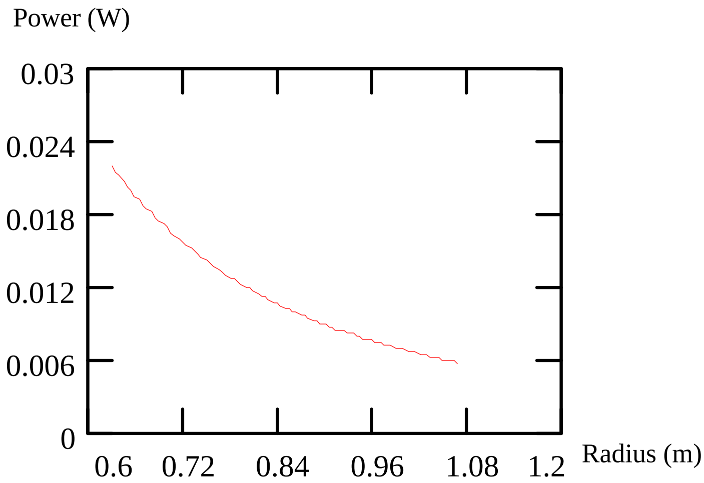

Figure 1: Heat dissipation per straw as a function of radius.

The above calculated heat dissipation and rates are the inputs in the calculations of the temperature distribution, cooling requirements, etc. throughout the paper.

2 Temperature Distribution in the Barrel TRT

Due to the heat produced in the straws and in absence of any internal cooling mechanism, the temperature will rise in the detector volume until a steady state is reached. The generated heat (Q) has the radial dependency calculated above i.e.,

$$Q(r) = \frac{q}{r^{2.51}}$$

Assuming a long hollow cylinder with outer (r = 1.07 m) and inner (r = 0.63 m) wall temperature of 20 ºC. The temperature as a function of radius can be calculated, assuming a mean thermal conductivity in the material, λ, equal to 0.05 W/m/K. The temperature equation in cylindrical coordinates

$$\frac{1}{r} \times \left[\frac{d}{dr} \times \left(r \times \frac{d}{dr} T(r) \right) \right] + \frac{q}{\lambda \times r^{2.51}} = 0 \tag{3}$$

gives the temperature distribution

$$T(r) = -2.353 \times \frac{\left[3181 + 1.799 \times \ln(r) \times r^{\left(\frac{51}{100}\right)} \right]}{r^{\left(\frac{51}{100}\right)}} + 7538 \tag{4}$$

shown in figure 2.

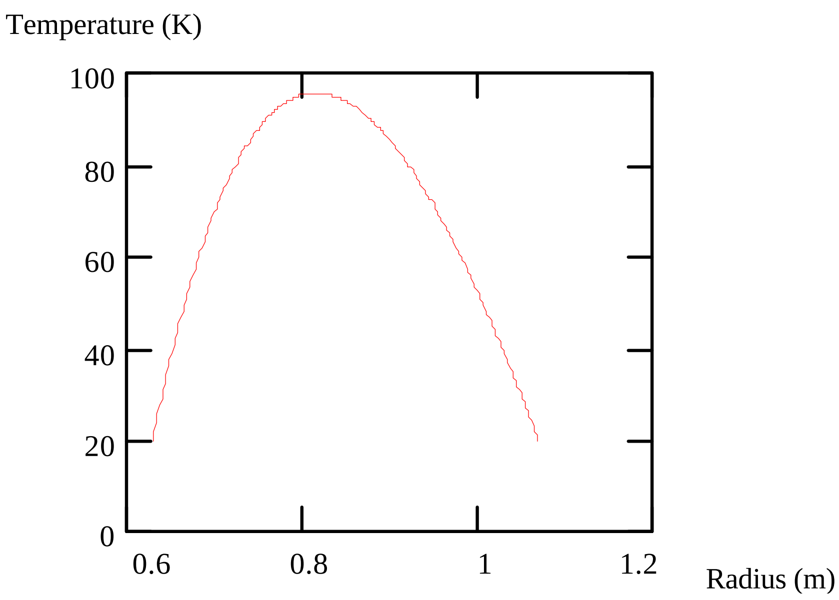

Figure 2: The temperature distribution in the barrel TRT assuming a long hollow cylinder with the boundaries fixed at 20 ºC.

This gives a maximum temperature difference of about 75 ºC. The calculation of T(r) is shown in more detail in Appendix A.

3 Constrains From Mechanical Tolerances

3.1 Detector Components

The most important task in designing the barrel TRT is to ensure stability of the wire positions down to 40 µm. Thermal expansion of the detector components will degrade the positioning of the wires and the detector performance. Detector components of interest are summarized in table 1 [2]. It is assumed that the temperature variation with time is not larger than the temperature differences inside the detector volume. The thermal elongation, Δl, is calculated from

$$\Delta l = \alpha \times l \times \Delta T \qquad (5)$$

where α is the coefficient of linear expansion.

Straw Walls

The reinforced straws are very resistant to temperature changes compared to the Kapton straw, as can be seen from table 1. For the reinforced straw this means a change in length of

$$\Delta l = 1K \times 1.6m \times 6 \times 10^{-6} / K \approx 10 \mu m \qquad (6)$$

for a temperature change of 1 ºC. A 100 µm change in straw length, corresponding to a temperature variation of 10 ºC is acceptable for the 1.6 m long barrel straws.

Component	Material	Thermal expansion coefficient (1/K)
Support structure	60% carbon fiber 40% epoxy	-0.42×10^{-6} / 30×10^{-6} (along /orthogonal to fiber)
Kapton straw (no reinforcement)	Kapton	3×10^{-4}
Reinforced straw	Kapton + carbon fiber + epoxy	6×10^{-6}
Anode wire	Cu-Be	16×10^{-6}
Anode wire	Tungsten	4.3×10^{-6}
Radiator	Polypropylene foam	120×10^{-6}

Table 1: Thermal expansion coefficients for different material in the barrel TRT.

Anode Wire
For the Cu-Be wire the thermal expansion is given by

$$\Delta l = 1K \times 1.6m \times 16 \times 10^{-6} \ / \ K \approx 26 \mu m \quad (7)$$

for a temperature change of 1 ºC.
A change in elongation for a 50 µm diameter wire then corresponds to a force (F) and

$$F = A \times E \times \Delta l = \pi \times r^2 \times E \times \Delta l \quad (8)$$

where E is Young's modulus for Cu-Be, r the wire radius and Δl the thermal expansion from (7). For $E = 21 \times 10^{10}$ N/m^2, r = 25 µm and Δl = 26 µm we obtain F = 0.010 N for 1 ºC temperature change, which is ~ 2 % of the wire tension if the wires are pretensioned to 50 g. A temperature change of 10 ºC should be acceptable.

Foam Radiator
The most worrying material from a mechanical point of view is the radiator. The radiator is made in blocks with precision drilled holes for the straws with a diameter of 4.8 mm. This leaves a clearance between a reinforced straw and radiator of 200 µm. The radiator is made in blocks, approximately 10 cm x 10 cm x 10 cm and the drilling accuracy is ~60 µm for the holes [4]. The elongation per 1 ºC over 10 cm foam is given by

$$\Delta l = 1K \times 0.1m \times 120 \times 10^{-6} \ / \ K \approx 12 \mu m \quad (9)$$

and with 10 ºC temperature change this is 120 µm. Taking into the account the drilling accuracy, a temperature change of 10 ºC is acceptable with a clearance of 200 µm. However, it should be noted that this acceptable temperature is critically dependent on the construction method chosen.

3.2 Support Structure

The support structure is somewhat decoupled from the problem of cooling the detector volume but, nevertheless the expected elongation from temperature changes is reported. It is reasonable to assume that the outer structure can be kept at a stable temperature. If one assumes that the carbon fiber direction can be chosen to decrease the effect of thermal expansion, then the main uncertainty is the effect of thermal expansion in the nodes, see figure 4. Taking a worst case where the nodes occupy 10% of the radial extension and a $\alpha = 30\text{x}10^{-6}$ /K. For a temperature change of 1 ºC the total elongation in r is

$$\Delta l = 1K \times 0.04m \times 30 \times 10^{-6} / K \approx 1.2\mu m . \qquad (10)$$

For a temperature change of 10 ºC, the upper limit for deformation is 12 µm, which is acceptable.

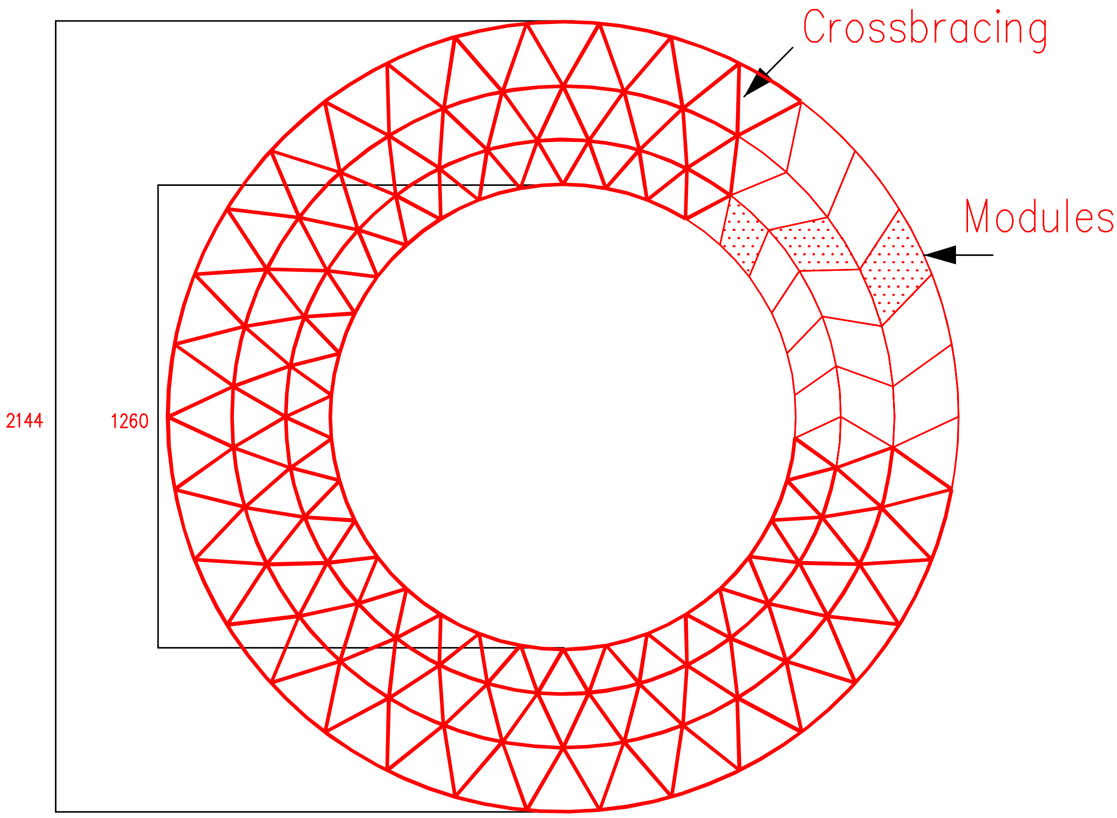

Figure 4: Support structure geometry for the barrel TRT.

4 Constrains From Straw Performance

To evaluate the cooling needs of the barrel TRT, it is necessary to investigate how temperature variations along the straws influence the physics performance. The gas gain uniformity should remain constant as far as possible. The question is; how do variations in gas temperature affect the gas gain? Resent results show that, for a gas gain of $3x10^4$, a gas gain dependency of 2.4 % / ºC for a 50 μm diameter wire and 1.5%/ ºC for a 30 μm wire [5].

4.1 Influence on Electron Identification

If we allow a change in gas gain of ~ 24% we get a limit on the gas gain of 10 ºC for the 50 μm wire and 15 ºC for the 30 μm wire. How the gas gain affects the electron identification is shown in figure 5, where the pion efficiency is shown as a function of gain variation along the in the barrel TRT, as estimated from test beam. A 25% gain variation is clearly acceptable and therefore also a 10 ºC temperature variation. If the gas gain is increased even further, the probability for streamer increases leading to heating and premature aging of the straws. Some margin is also necessary as there are other effects that alter gas uniformity, for example deflection of the anode wire, bending in the straws etc.

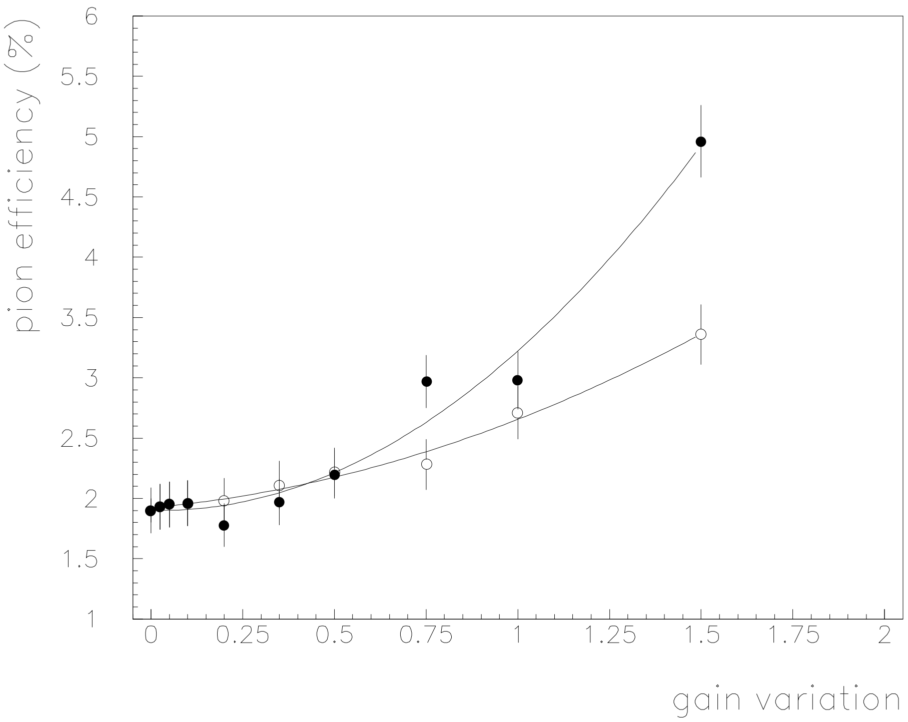

Figure 5. Pion efficiency as function of change in gas gain
• constant threshold
º threshold optimized for running conditions

4.2 Drift Time Accuracy

A gain variation corresponds to a variation threshold for drift time measurements. How this affects the resolution is shown in figure 6. A gain variation of 25 % will change the resolution with 10 μm, which is neglectable. A 10 ºC temperature variation is therefore acceptable.

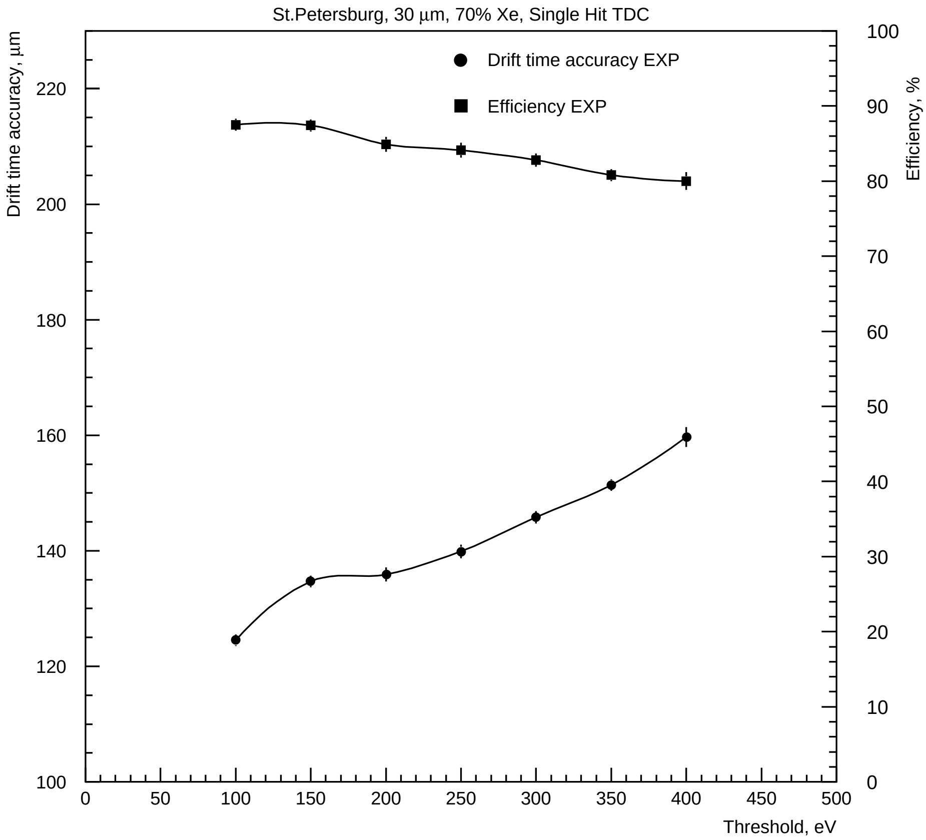

Figure 6. Drift time accuracy as a function of discriminator threshold [6].

5 Cooling Requirements and Schemes

5.1 Introduction

Several sources contribute to the error of wire positioning and straw performance and the errors caused by the temperature differences should be kept small compared to these. The requirements above give an acceptable temperature difference of about 10 ºC and figure 2 in section 2 shows clearly the need of cooling inside the detector volume. Three possible ways for cooling are described below. For simplicity CO_2 is used for cooling outside the straws and Xe is used in the calculation of cooling with the detector gas.

5.1 Cooling Module Boundaries

If the same calculation of section 2 is carried out for the inner module i.e., T(r = 0.630 m) = T(r = 0.752 m) = 20 ºC, the maximum temperature difference in r is then reduced to below 10 ºC (see figure 7). The calculation is made for the inner module as it is the most critical because of the high rate. Additional cooling can be obtained by cooling all four sides of the module and this will decrease the radial temperature difference in the module below 5 ºC.

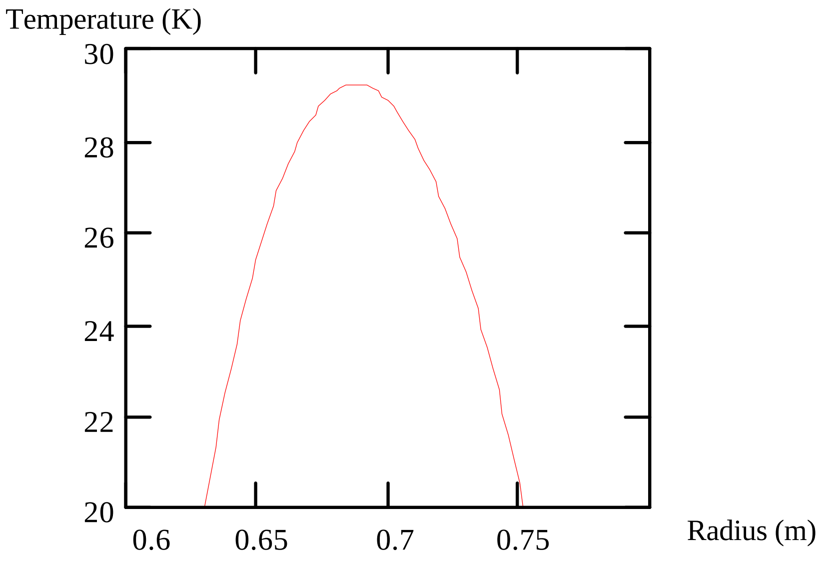

Figure 7: The temperature distribution for an inner module with an inner outer radius of 0.63 m and 0.752 m respectively.

5.2 Cooling Individual Straws

Two possible ways of cooling the straws with a flow of gas have been studied. In one scheme the detector gas (Xe) is used. A second scheme uses CO_2 that is blown outside, along the straws to maintain the temperature difference in the straw below 10 ºC. The required gas flow per straw as a function of radius is shown in figure 8 and is obtained from

$$W = C_p \times \dot{M} \times \Delta T \tag{11}$$

where W is the power dissipation, C_p is the specific heat, $\dot{M}$ is the gas flow in mass per second. The total power dissipation of 574 W gives a total gas flow of 0.07 kg/s of CO_2 and 0.342 kg/s of Xe i.e., 41 l/s and 63 l/s at NPT. This is if one uses only the detector gas as cooling method. More details can be found in Appendix B. This values assume an optimized gas flow through the detector according to figure 8.

5.2.1 Cooling With the Detector Gas

One problem with this system is to find enough pumping power (dry pumps) for this high gas flow. The maximum pumping capacity that has so far been found on the market is ~ 3.3 l/s (at 1 bar). The pressure drops are significantly higher in the pipe work, 5.6 times, for the same cooling power with Xe (table 2). This means more space and material is required with Xe gas cooling.

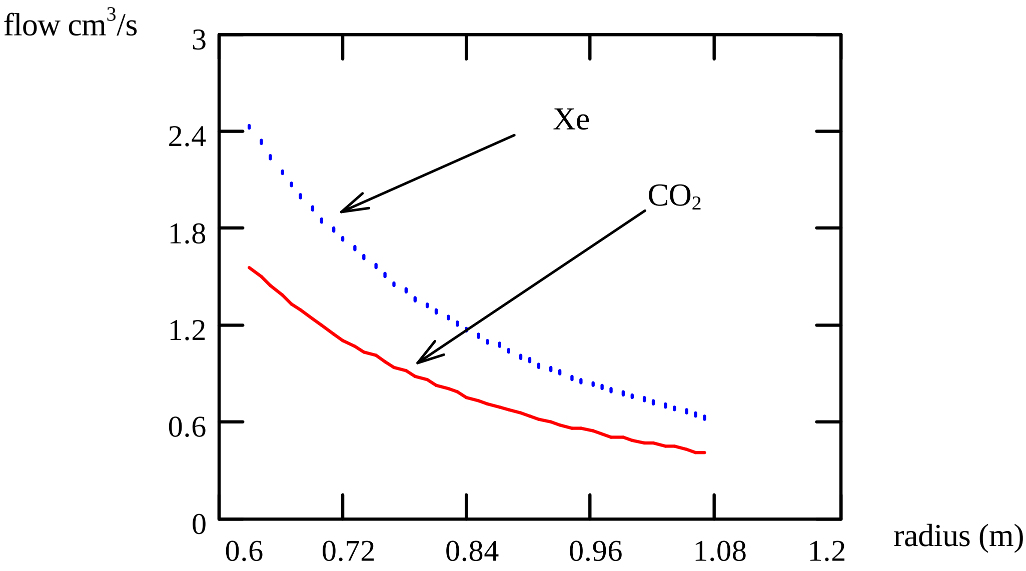

Figure 8. Required gas flow per straw as a function of radius with a maximum ΔT = 10 ºC along the straws.

5.2.2 Cooling With CO_2 Outside the Straws

Another way of cooling the straws is to blow CO_2 between the straws and the foam. The holes in the foam are assumed to be 4.8 mm in diameter and this gap allows a flow of gas around each straw. A flow of 41 l/s NPT for the hole detector is needed for a temperature difference of 10 ºC (section 5.2). The pressure drop in the detector volume i.e., between the straws and the foam in the case of CO_2 cooling is small. Calculation of the pressure drop is performed in Appendix C. Experimental values confirm these calculations [4]. The flow around the straws can be decreased by a factor two by having input at both ends of the detector and output in the middle (z = 0). The *total* gas flow in and out of the detector volume of course stays the same. With CO_2 cooling, standard compressors can be used to circulate the gas as the purity demands are smaller and high flow can easily be obtained. The cleaning of the radiator from Xe is done with the cooling gas.

6 Service Estimate

In figure 9 the pipe work to bring in the cooling gas to the detector area is shown and the different sections are market with numbers. The gas input is assumed to be at one end of the detector and the output at the other end. The pipe dimensions, bending etc. are summarized together with the pressure drops in table 2. It is far from complete (no branches for example) but it gives an idea of the pressure drop in the services. The calculation is done until the crack region were a more detailed study of the gas distribution system is required. More details on the calculations of the pressure drops are given in Appendix D.

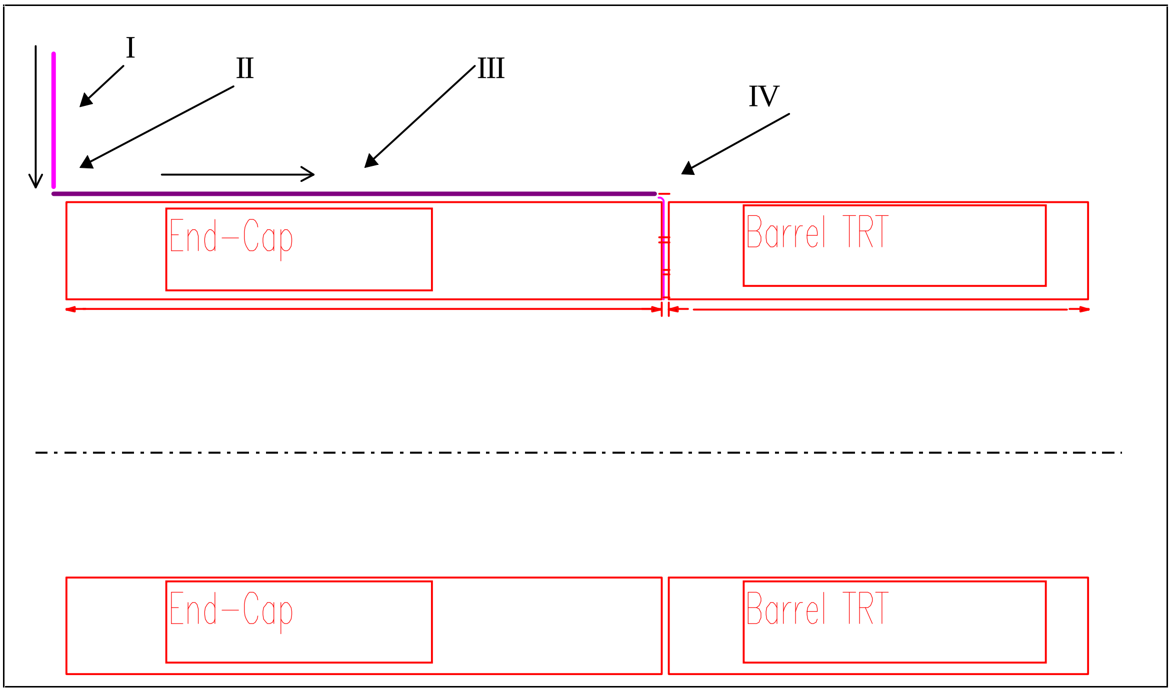

Figure 9: Pipe work in the inner detector with the different sections I-VI. The pressure drops are summarized in table 2.

Section	n=number of pipes l=length, d=diameter r=bending radius	Xe 63 l/s	CO_2 41 l/s
I) Straight section	n=2, l =20m, d=7.3cm	7.5	1.4
II) Bending	n=2, r=10cm, d=7.3cm	0.23	0.03
III) Straight section	n=16, l=240, d=2.5cm,	3.8	0.7
IV) Bending	n=32, r=3 cm, d=1.7cm	0.27	0.03
	Total pressure drop (mbar):	12	2.2

Table 2 : An example of pipe work for the barrel TRT cooling showing the pressure drops (mbar) in different sections.

Conclusions

An active cooling is needed to bring down the temperature differences in the straws to an acceptable value. A flow of CO_2 gas outside the straws or cooling the module boundaries seems preferable.

References

1.) Simulation of the TRT System Rate Response and Occupancy, F. C. Luehring, G. G. Hanson, H. O. Ogren, D. R. Rust, ATLAS INDET No-081, 1994

2.) Systematic study of straw proportional tubes for the ATLAS Inner Detector, RD6 Collaboration, ATLAS INDET No-18, 1993.

3) A Modular Structure for the Barrel TRT, H. Danielsson, M. Price, T. Åkesson, Technical Note TA1/94-31.

4) Design Considerations for the foam structure in the Barrel TRT,G. Gillessen, M. Holder, A. Kreutz, Fachbereich Physik, University of Siegen, ATLAS INDET-NO-

5) Private communication with B. Dolgoshshein, Anatoli Romaniuk, Moscow Physical Engineering Institute

6) Straw and front-end electronics performance at high counting rates, A. Romaniouk, E. Spiridenkov, ATLAS INDET-NO-079, 06-12-94

Appendix A

Temperature Profile in the barrel-TRT

Suppose we have a heat dissipation proportional to 1/r^2.51

We know the heat dissipation on the inner straws are 0.022 mW/straw
and we get:

$qs := 0.022 \cdot 0.63^{2.51}$

$Q(r) := \frac{qs}{r^{2.51}}$

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$Ri := 0.63$ inner radius

$Ro := 1.07$ outer radius

$l := 1.6$ length of the barrel

$n := 50048$ number of straws

Know we calculate the *mean* heat dissipation in the straws:

$$qm := \frac{1}{Ro - Ri} \cdot \int_{Ri}^{Ro} \frac{qs}{r^{2.51}}\,dr \qquad qm = 0.01149 \qquad P := n \cdot qm$$

This give the total generated heat in the barrel; $P = 574.85086$ (W)

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and the *total* heat dissipation of 1 m barrel : $P := n \cdot \frac{qm}{l}$ ===> $P = 359.28179$ (W)

We know from above that the heat dissipation is proportional to 1/r^2.51
and we take the integral to find a uniformly generated heat q.

$$P = \int_{Ro}^{Ri} \frac{q}{r^{2.51}}\,dA$$

where dA=2*π*r*dr

this gives:

$$q := \frac{P}{\frac{12.32}{Ri^{\left(\frac{51}{100}\right)}} - \frac{12.32}{Ro^{\left(\frac{51}{100}\right)}}}$$

From temperature equation and cylindrical coordinates we have: $q = 97.32717$ (W/m^2)

$$\frac{1}{r} \cdot \left[\frac{d}{dr}\left(r \cdot \frac{d}{dr}T(r)\right)\right] + \frac{\alpha}{r^{2.51}} = 0$$ and with

$\lambda := 0.05$ (W/m*K)

$\alpha := \frac{q}{\lambda}$

$Ri := 0.63$

$Ro := 1.07$

we finally get (after some integration):

$$\left[\frac{d}{dr}\left(r \cdot \frac{d}{dr}T(r)\right)\right] = -\frac{\alpha}{r^{1.51}} \quad ====> \quad r \cdot \frac{d}{dr}T(r) = \frac{1.9608}{r^{\left(\frac{51}{100}\right)}} \cdot \alpha + A$$

$$\frac{d}{dr}T(r) = \frac{1.9608}{r^{\left(\frac{51}{100}+1\right)}} \cdot \alpha + \frac{A}{r} \quad ====> \quad T(r) = -2.35310^{-3} \cdot \frac{\left[1634 \cdot \alpha - 425 \cdot A \cdot \ln(r) \cdot r^{\left(\frac{51}{100}\right)}\right]}{r^{\left(\frac{51}{100}\right)}} + B$$

Boundary conditions: $T(Ri) = 20$ and $T(Ro) = 20$

$$20 = -2.353\cdot 10^{-3}\cdot\frac{\left[1634\cdot\alpha - 425\cdot A\cdot\ln(Ro)\cdot Ro^{\left(\frac{51}{100}\right)}\right]}{Ro^{\left(\frac{51}{100}\right)}} + B$$

====>

$$20 = -2.353\cdot 10^{-3}\cdot\frac{\left[1634\cdot\alpha - 425\cdot A\cdot\ln(Ri)\cdot Ri^{\left(\frac{51}{100}\right)}\right]}{Ri^{\left(\frac{51}{100}\right)}} + B$$

====>

$$A := \frac{1634}{425}\cdot\alpha\cdot\frac{\frac{1}{Ro^{\frac{51}{100}}} - \frac{1}{Ri^{\frac{51}{100}}}}{\ln\left(\frac{Ro}{Ri}\right)}$$

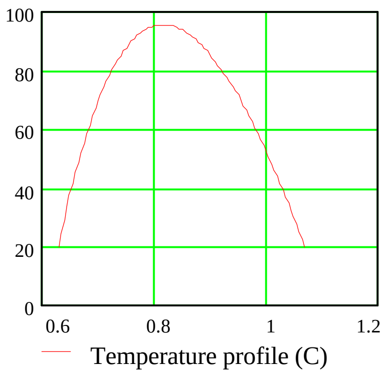
$$B := 20 + 2.353\cdot 10^{-3}\cdot\frac{\left[1634\alpha - 425\cdot A\cdot\ln(Ri)\cdot Ri^{\left(\frac{51}{100}\right)}\right]}{Ri^{\left(\frac{51}{100}\right)}}$$

and finally;

$$T(r) = -2.353\cdot 10^{-3}\cdot\frac{\left[1634\alpha - 425\cdot A\cdot\ln(r)\cdot r^{\left(\frac{51}{100}\right)}\right]}{r^{\left(\frac{51}{100}\right)}} = -2.353\,\frac{\left[3181 + 1799\ln(r)\cdot r^{\left(\frac{51}{100}\right)}\right]}{r^{\left(\frac{51}{100}\right)}} + 7538.$$

==

$h := 0.63, 0.635 .. 1.07$



>>> Maximum temperature difference in barrel > 70 K (i.e. close to "back of the envelope" calculations) and to high

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Comments: here we have used a mean power dissipation along the straws of 22 mW but it might be higher for some z. Also we haven't taken into account cooling along the Z-axis. We will probably be helped in some way by this, but the detector length is 4 times the radial length and the straws itself contributes very little.

Appendix B

Cooling requirements with Xe inside the straws or CO_2 outside the straws

Mean power in the barrel straws (W)	$W := 574 \cdot \frac{kg \cdot m^2}{sec^3}$	
Acceptable temperature difference (K)	$dT := 10 \cdot K$	
Density	$\rho CO2 := 1.977 \cdot \frac{kg}{m^3}$	$\rho Xe := 5.890 \cdot \frac{kg}{m^3}$
Viscosity (Ns/m ^{2})	$\mu CO2 := 13.9 \cdot 10^{-6} \cdot \frac{kg}{m \cdot sec}$	$\mu Xe := 22.6 \cdot 10^{-6} \cdot \frac{kg}{m \cdot sec}$
Specific heat	$CpCO2 := 0.82 \cdot 10^3 \cdot \frac{m^2}{sec^2 \cdot K}$	$CpXe := 0.168 \cdot 10^3 \cdot \frac{m^2}{sec^2 \cdot K}$
Atomic mass (kg/mol)	$MCO2 := 0.042 \cdot kg$	$MXe := 0.1313 \cdot kg$
Pressure (Pa,N/m^2)	$P := 1 \cdot 10^5 \cdot \frac{kg}{m \cdot sec^2}$	
Gas constant (J/mol/K)	$R := 8.314 \cdot \frac{kg \cdot m^2}{sec^2 \cdot K}$	
Absolute temperature (K)	$T := 293 \cdot K$	

$$massCO2 := \frac{W}{CpCO2 \cdot dT} \qquad massXe := \frac{W}{CpXe \cdot dT}$$

$$massCO2 = 0.07 \cdot kg \cdot sec^{-1} \qquad massXe = 0.342 \cdot kg \cdot sec^{-1}$$

$$QCO2 := \frac{massCO2 \cdot R \cdot T}{P \cdot MCO2} \qquad QXe := \frac{massXe \cdot R \cdot T}{P \cdot MXe}$$

==> $QCO2 = 0.041 \cdot m^3 \cdot sec^{-1}$ ==> $QXe = 0.063 \cdot m^3 \cdot sec^{-1}$

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Appendix C

Calculation of pressure drop with Xe inside the straws or CO_2 outside the straws.

The generated power in the straws, 1.6 m long, is assumed to be 11 mW with a maximum temperature difference of 10 K. The gas is assumed to be CO_2 and we have the following parameters:

Power/straw (W)	$W := \frac{0.022}{2} \cdot kg \cdot \frac{m^2}{sec^3}$
diameter (m)	$d := 0.004 m$
straw length (m)	$l := 0.8 \cdot m$
temperatur difference (K)	$dT := 10 \cdot K$
viscosity (Ns/m²)	$\mu := 13.9 \cdot 10^{-6} \cdot \frac{kg}{m \cdot sec}$
density (kg/m³)	$\rho := \frac{1.977 \cdot kg}{m^3}$
specific heat (J/kg/K)	$Cp := 0.82 \cdot 10^3 \cdot \frac{m^2}{sec^2 \cdot K}$
molecular weight (kg/mol)	$M := 0.042 kg$
pressure (Pa,N/m²)	$P := 1 \cdot 10^5 \cdot \frac{kg}{m \cdot sec^2}$

} Carbondioxide

Gas constant (J/mol/K) $R := 8.314 kg \cdot \frac{m^2}{sec^2 \cdot K}$

temperature (K) $T := 293 K$

The cooling power in the gas is given by:

$$W = m \cdot Cp \cdot dT$$

And to get the mass flow we take:

$$mass := \frac{W}{Cp \cdot dT} \qquad mass = 1.341 \cdot 10^{-6} \cdot kg \cdot sec^{-1}$$

Now we can calculate the flow rate per straw:

$$P \cdot Q = \frac{m}{M} \cdot R \cdot T \qquad ==>$$

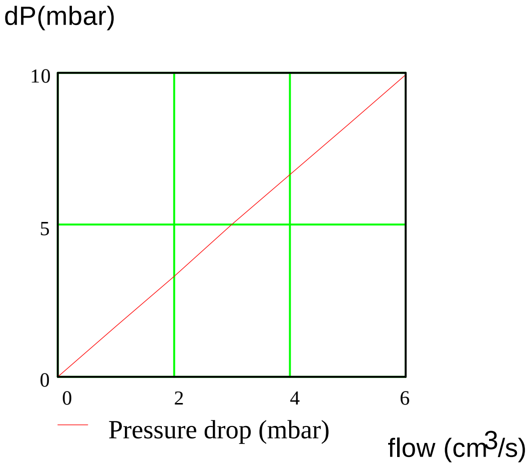
$$Q := \frac{mass \cdot R \cdot T}{P \cdot M} \qquad ==> \qquad Q = 7.78 \cdot 10^{-7} \cdot m^3 \cdot sec^{-1}$$

Now we would like to calculate the pressure drop when the straw is cooled from the outside in a small gap between the straw and the foam.

To be able to calculate the pressure drop, dP(mbar) in a small gap, c (m), we have:

$$Q = \frac{dP \cdot \pi \cdot d \cdot c^3}{12 \cdot \mu \cdot l} \qquad c := 0.40 \cdot 10^{-3} \cdot m \qquad n := 0, 1..6 \qquad ==> \qquad dP := \frac{Q \cdot 12 \cdot \mu \cdot l}{\pi \cdot d \cdot c^3}$$

$$1mbar = 100 \cdot \frac{N}{m^2} = 100 \cdot \frac{kg}{m \cdot s^2} \qquad dP = 129.093 \cdot kg \cdot m^{-1} \cdot sec^{-2}$$



$$u := \frac{Q}{\pi \cdot \left[\left(\frac{d + c}{2} \right)^2 - \left(\frac{d}{2} \right)^2 \right]}$$

$u = 0.295 \, m \cdot sec^{-1}$

$$Re := \pi \cdot d \cdot u \cdot \frac{\rho}{\mu}$$

$Re = 526.963$

What will happen if we cool inside the straw using the Xenon gas?

For Xenon we have the following parameters:

viscosity (Ns/m^2)	$\mu := 22.6 \cdot 10^{-6} \cdot \frac{kg}{m \cdot sec}$	Xenon
density (kg/m^3)	$\rho := 5.890 \cdot \frac{kg}{m^3}$	
specific heat (J/kg*K)	$Cp := 0.168 \cdot 10^3 \cdot \frac{m^2}{sec^2 \cdot K}$	
atomic mass (kg/mol)	$M := 0.1313 \cdot kg$	
pressure (Pa,N/m^2)	$P := 1 \cdot 10^5 \cdot \frac{kg}{m \cdot sec^2}$	
temperature (K)	$T := 293 \cdot K$	
length (m)	$l := 1.6 \cdot m$	

First we calculate the mass flow as before:

$mass := \frac{W}{Cp \cdot dT}$ $\quad mass = 6.548 \cdot 10^{-6} \cdot kg \cdot sec^{-1}$

(Note that the straw length is from one end of the detector to the other! i.e. 2*l)

Now we can calculate the mean flow rate per straw:

$P \cdot Q = \frac{m}{M} \cdot R \cdot T$ ==> $Q := \frac{mass \cdot R \cdot T}{P \cdot M}$

==> $Q = 1.215 \cdot 10^{-6} \cdot m^3 \cdot sec^{-1}$

The mean velocity u (m/s) in the straw is given by:

$u := \frac{Q}{\pi \cdot \left(\frac{d}{2}\right)^2}$ ==> $u = 0.0967 \cdot m \cdot sec^{-1}$

The Reynolds number (Re) for a circular pipe is given by:

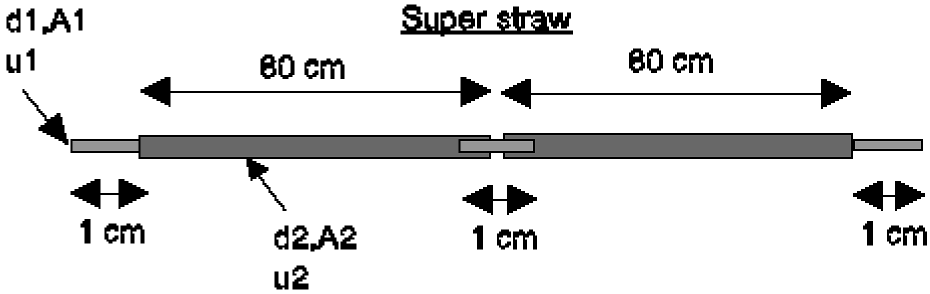
$Re := d \cdot u \cdot \frac{\rho}{\mu}$ ==> $Re = 100.775$

The pressure drop in a straw (2*l) is given by: (laminar flow)

$dP := 4 \cdot l \cdot \left(\frac{16}{Re}\right) \cdot \frac{\rho}{d} \cdot \frac{u^2}{2}$ ==> $dP = 6.991 \cdot kg \cdot m^{-1} \cdot sec^{-2}$

What will happen with the pressure drop over the endplugs?

Suppose we have endplugs that are 10 mm long and with a cross-section that corresponds to a hole with a diameter of 0.5 mm. We also have a piece between the two straws which is assumed to have the same dimensions as the endplugs.



diameter of the endplugs (m) $d1 := 0.0005m$

length of the endplugs (m) $h := 0.010m$

Note that the flow becomes turbulent beyond ~ Re = 2000.
The pressure drop per endplug follows from:

$$u := \frac{Q}{\pi\cdot\left(\frac{d1}{2}\right)^2} \quad ==> \quad u = 6.187\,m\cdot sec^{-1} \qquad Re := d1\cdot u\cdot\frac{\rho}{\mu}$$

$$==> \quad Re = 806.201$$

$$dPp := 4\cdot h\cdot\left(\frac{16}{Re}\right)\cdot\frac{\rho}{d1}\cdot\frac{u^2}{2} \quad ==> \quad dPp = 178.972\,kg\cdot m^{-1}\cdot sec^{-2}$$

$$dPp := 4\cdot h\cdot\left(\frac{0.079}{Re^{\frac{1}{4}}}\right)\cdot\frac{\rho}{d1}\cdot\frac{u^2}{2} \qquad dPp = 133.698\,kg\cdot m^{-1}\cdot sec^{-2}$$

The loss of head also occurs in outlets and inlets and this is calculated below. We have one abrupt enlargement and one abrupt contraction per end of the straw, see figure above., dPe stands for the pressure drop in the abrupt enlargements and dPc for the pressure drop in the abrupt contraction

Weight per unit mass (m/s^2) and $Q = 1.215\cdot 10^{-6}\cdot m^3\cdot sec^{-1}$

$d1 = 5\cdot 10^{-4}\cdot m$ $\qquad d2 := d$

$$A1 := \pi\cdot\left(\frac{d1}{2}\right)^2 \quad A1 = 1.963\cdot 10^{-7}\cdot m^2 \qquad A2 := \pi\cdot\left(\frac{d2}{2}\right)^2 \quad A2 = 1.257\cdot 10^{-5}\cdot m^2$$

$$u1 := \frac{Q}{\pi\cdot\left(\frac{d1}{2}\right)^2} \quad u1 = 6.187\,m\cdot sec^{-1} \qquad u2 := \frac{Q}{\pi\cdot\left(\frac{d2}{2}\right)^2} \quad u2 = 0.097\,m\cdot sec^{-1}$$

In the worst case (intake and outlet) we have : $A2 := \infty\cdot m^2$

$$Headloss = k \cdot \frac{u^2}{2 \cdot g} \qquad k := \left(1 - \frac{A1}{A2}\right)^2 \qquad ==> \qquad k = 1$$

$$dPe := k \cdot \frac{u1^2}{2} \cdot \rho \qquad dPe = 112.7245 \, kg \cdot m^{-1} \cdot sec^{-2}$$ for one enlargement.

For the abrupt contractions we have (u is again u the from the narrow side i.e. u1):.

$$Headloss = k \cdot \frac{u^2}{2 \cdot g}$$ With $d2 := \infty \cdot m$ we get $k := 0.5$ for the worst case

and

$$dPc := k \cdot \frac{u1^2}{2} \cdot \rho \qquad dPc = 56.362 \, kg \cdot m^{-1} \cdot sec^{-2}$$ for one contraction.

With $d2 := d$ and $d1 := 0.5 \cdot 10^{-3} \cdot m$ we have $\frac{d1}{d2} = 0.125$ and k=0.4 (from Massey)

By assuming we have the same dimensions for all three plastic plugs as as the flow is concerned we get three enlargements (dPe) , three contractions (dPc) and three 1cm long "pipes" (dPp).dP is the pressure drop over the straw.

$$dPtot := 3 \cdot dPp + 3 \cdot dPc + 3 \cdot dPe + dP \qquad dPtot = 915.345 \, kg \cdot m^{-1} \cdot sec^{-2}$$

Now we'll try different dimensions, i.e different d1 with a flow (Q) as calculated above.

Through the plug: $n := 0, 1 .. 4$ $\qquad Q = 1.215 \cdot 10^{-6} \cdot m^3 \cdot sec^{-1}$

$$Re_n := d1_n \cdot \frac{Q}{\pi \cdot \left(\frac{d1_n}{2}\right)^2} \cdot \frac{\rho}{\mu}$$

$d1_n :=$

0.0002m
0.0005m
0.001m
0.0018m
0.003m

Re_n

$2.016 \cdot 10^3$
806.201
403.1
223.945
134.367

$$dPtp_n := 4 \cdot h \cdot \left[\frac{0.079}{\left(Re_n\right)^{\frac{1}{4}}}\right] \cdot \frac{\rho}{d1_n} \cdot \frac{\left[\frac{Q}{\pi \cdot \left(\frac{d1_n}{2}\right)^2}\right]^2}{2}$$

$dPtp_n$

$1.038 \cdot 10^4 \cdot kg \cdot m^{-1} \cdot sec^{-2}$
$133.698 \, kg \cdot m^{-1} \cdot sec^{-2}$
$4.969 \, kg \cdot m^{-1} \cdot sec^{-2}$
$0.305 \, kg \cdot m^{-1} \cdot sec^{-2}$
$0.027 \, kg \cdot m^{-1} \cdot sec^{-2}$

Enlargement: $k := 1$

$$dPe_n := k \cdot \frac{\left[\frac{Q}{\pi \cdot \left(\frac{d1_n}{2}\right)^2}\right]^2}{2} \cdot \rho$$

dPe_n

$4.403 \cdot 10^3 \cdot kg \cdot m^{-1} \cdot sec^{-2}$
$112.724 \, kg \cdot m^{-1} \cdot sec^{-2}$
$7.045 \, kg \cdot m^{-1} \cdot sec^{-2}$
$0.671 \, kg \cdot m^{-1} \cdot sec^{-2}$
$0.087 \, kg \cdot m^{-1} \cdot sec^{-2}$

Contraction: $k := 0.5$ (Worst case!)

$$dPc_n := k \cdot \frac{\left[\frac{Q}{\pi \cdot \left(\frac{d1_n}{2}\right)^2}\right]^2}{2} \cdot \rho$$

dPc_n

$2.202 \cdot 10^3 \cdot kg \cdot m^{-1} \cdot sec^{-2}$
$56.362 \, kg \cdot m^{-1} \cdot sec^{-2}$
$3.523 \, kg \cdot m^{-1} \cdot sec^{-2}$
$0.336 \, kg \cdot m^{-1} \cdot sec^{-2}$
$0.043 \, kg \cdot m^{-1} \cdot sec^{-2}$

Total:

$$dPtot_n := 3 \cdot dPtp_n + 3 \cdot dPe_n + 3 \cdot dPc_n + dP$$

$$1mbar = 100 \frac{N}{m^2} = 100 \frac{kg}{m \cdot s^2}$$

$dPtot_n$

$5.097 \cdot 10^4 \cdot kg \cdot m^{-1} \cdot sec^{-2}$
$915.345 \, kg \cdot m^{-1} \cdot sec^{-2}$
$53.601 \, kg \cdot m^{-1} \cdot sec^{-2}$
$10.925 \, kg \cdot m^{-1} \cdot sec^{-2}$
$7.463 \, kg \cdot m^{-1} \cdot sec^{-2}$

The cross-section of the plastic plug is (maximum available):

$$s := \pi \cdot \left(\frac{2.5 \cdot 10^{-3} \cdot m}{2}\right)^2 \qquad s = 4.909 \cdot 10^{-6} \, m^2 \qquad A_n := \pi \cdot \left(\frac{d1_n}{2}\right)^2$$

Opening for gas flow

A_n

$3.142 \cdot 10^{-8} \cdot m^2$
$1.963 \cdot 10^{-7} \cdot m^2$
$7.854 \cdot 10^{-7} \cdot m^2$
$2.545 \cdot 10^{-6} \cdot m^2$
$7.069 \cdot 10^{-6} \cdot m^2$

$$Rel_n := \frac{A_n}{s} \cdot 100 \qquad (\%)$$

Conclusion:

$d1_n$	$dPtot_n$	Rel_n (%)
$2 \cdot 10^{-4} \cdot m$	$5.097 \cdot 10^4 \cdot kg \cdot m^{-1} \cdot sec^{-2}$	0.64
$5 \cdot 10^{-4} \cdot m$	$915.345 \, kg \cdot m^{-1} \cdot sec^{-2}$	4
0.001 m	$53.601 \, kg \cdot m^{-1} \cdot sec^{-2}$	16
0.0018 m	$10.925 \, kg \cdot m^{-1} \cdot sec^{-2}$	51.84
0.003 m	$7.463 \, kg \cdot m^{-1} \cdot sec^{-2}$	144

Appendix D

Example of calculation of pressure drops and size of barrel TRT services .

The calculation is divided into the following parts:

1) Straight section: d1 = 73 mm, l1 = 20 m
2) Bending with r1= 10 cm, 90 degree, d2=2.5
3) Straight section d = 25 mm , l = 2.37 m
4) bending with r = 3 cm, 90 degree, d3=1.7cm

From before we have for Xe (Appendix A):

viscosity (Ns/m^2) $\mu := 22.6\,10^{-6}\cdot\frac{kg}{m\cdot sec}$

density (kg/m^3) $\rho := 5.890\frac{kg}{m^3}$ $Q := 0.06356\frac{m^3}{sec}$

$d1 := 0.073m$ $l1 := 20\cdot m$ $N1 := 2$

1) $A1 := N1\cdot\pi\cdot\left(\frac{d1}{2}\right)^2$ $A1 = 0.008\,m^2$

Gas speed in the pipes: $u_1 := \frac{Q}{A1}$ $u_1 = 7.593\,m\cdot sec^{-1}$

The Reynolds number (Re) for a circular pipe is given by:

$Re := d1\cdot u_1\cdot\frac{\rho}{\mu}$ ==> $Re = 1.445\cdot 10^5$

$$dP_1 := 4\cdot l1\cdot\left(\frac{0.079}{Re^{\frac{1}{4}}}\right)\cdot\frac{\rho}{d1}\cdot\frac{\left(u_1\right)^2}{2}$$

$dP_1 = 754.013\,kg\cdot m^{-1}\cdot sec^{-2}$

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2) Bending with r = 10 cm, 90 degree. 16 pipes with diameter 2.5 cm

$d2 := 0.025m$ $r1 := 0.10m$ $N2 := 16$

$k := \frac{r1}{d2}$ $k = 4$ from diagram we have $\zeta := 0.12$

$A2 := N2\cdot\pi\cdot\left(\frac{d2}{2}\right)^2$ $A2 = 0.008\,m^2$ $u_2 := \frac{Q}{A2}$ $u_2 = 8.093\,m\cdot sec^{-1}$

$dP_2 := \zeta\cdot\frac{\rho\cdot\left(u_2\right)^2}{2}$ $dP_2 = 23.145\,kg\cdot m^{-1}\cdot sec^{-2}$

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3) 16 pipes with d = 25 mm , l = 2.37 m $\quad l2 := 2.37 \cdot m$

$$Re := d2 \cdot u_2 \cdot \frac{\rho}{\mu} \quad ==> \quad Re = 5.309 \cdot 10^4$$

$$dP_3 := 4 \cdot l2 \cdot \left(\frac{0.079}{Re^{\frac{1}{4}}} \right) \cdot \frac{\rho}{d2} \cdot \frac{(u_2)^2}{2}$$

$$dP_3 = 385.924 \, kg \cdot m^{-1} \cdot sec^{-2}$$

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4) Bending with r = 3 cm, 90 degree $\quad d3 := 0.017 \, m \quad r2 := 0.03 \, m \quad N3 := 32$

$$\frac{r2}{d3} = 1.765 \quad ====> \quad \zeta := 0.14$$

$$A3 := N3 \cdot \pi \cdot \left(\frac{d3}{2} \right)^2 \quad A3 = 0.007 \, m^2 \quad u_3 := \frac{Q}{A3} \quad u_3 = 8.811 \, m \cdot sec^{-1}$$

$$dP_4 := \zeta \cdot \frac{\rho \cdot (u_2)^2}{2} \quad dP_4 = 27.377 \, kg \cdot m^{-1} \cdot sec^{-2}$$

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$$dPtot := \frac{(dP_1 + dP_2 + dP_3 + dP_4) \cdot m \cdot \frac{sec^2}{kg}}{100}$$

Total pressure drop in mbar : $dPtot = 11.999$

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From before we have for CO_2 (Appendix A):

viscosity (Ns/m^2) $\mu := 13.9 \cdot 10^{-6} \cdot \frac{kg}{m \cdot sec}$

density (kg/m^3) $\rho := 1.977 \cdot \frac{kg}{m^3}$ $Q := 0.041 \cdot \frac{m^3}{sec}$

$d1 := 0.073 m$ $l1 := 20 \cdot m$ $N1 := 2$

1) $A1 := N1 \cdot \pi \cdot \left(\frac{d1}{2}\right)^2$ $A1 = 0.008 \, m^2$

Gas speed in the pipes: $u_1 := \frac{Q}{A1}$ $u_1 = 4.898 \, m \cdot sec^{-1}$

The Reynolds number (Re) for a circular pipe is given by:

$Re := d1 \cdot u_1 \cdot \frac{\rho}{\mu}$ ==> $Re = 5.085 \cdot 10^4$

$$dP_1 := 4 \cdot l1 \cdot \left(\frac{0.079}{Re^{\frac{1}{4}}}\right) \cdot \frac{\rho}{d1} \cdot \frac{(u_1)^2}{2}$$

$dP_1 = 136.718 \, kg \cdot m^{-1} \cdot sec^{-2}$

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2) Bending with r = 10 cm, 90 degree. 16 pipes with diameter 2.5 cm

$d2 := 0.025 m$ $r1 := 0.10 m$ $N2 := 16$

$k := \frac{r1}{d2}$ $k = 4$ from diagram we have $\zeta := 0.12$

$A2 := N2 \cdot \pi \cdot \left(\frac{d2}{2}\right)^2$ $A2 = 0.008 \, m^2$ $u_2 := \frac{Q}{A2}$ $u_2 = 5.22 \, m \cdot sec^{-1}$

$dP_2 := \zeta \cdot \frac{\rho \cdot (u_2)^2}{2}$ $dP_2 = 3.233 \, kg \cdot m^{-1} \cdot sec^{-2}$

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3) 16 pipes with d = 25 mm , l = 2.37 m $l2 := 2.37 \cdot m$

$Re := d2 \cdot u_2 \cdot \frac{\rho}{\mu}$ ==> $Re = 1.856 \cdot 10^4$

$$dP_3 := 4 \cdot l2 \cdot \left(\frac{0.079}{Re^{\frac{1}{4}}} \right) \cdot \frac{\rho}{d2} \cdot \frac{(u_2)^2}{2}$$

$dP_3 = 69.136 \cdot kg \cdot m^{-1} \cdot sec^{-2}$

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4) Bending with r = 3 cm, 90 degree $d3 := 0.017 \cdot m$ $r2 := 0.03 m$ $N3 := 32$

$\frac{r2}{d3} = 1.765$ ====> $\zeta := 0.14$

$A3 := N3 \cdot \pi \cdot \left(\frac{d3}{2} \right)^2$ $A3 = 0.007 \cdot m^2$ $u_3 := \frac{Q}{A3}$ $u_3 = 5.645 \cdot m \cdot sec^{-1}$

$dP_4 := \zeta \cdot \frac{\rho \cdot (u_2)^2}{2}$ $dP_4 = 3.771 \cdot kg \cdot m^{-1} \cdot sec^{-2}$ $dPtot := \frac{(dP_1 + dP_2 + dP_3 + dP_4) \cdot m \cdot \frac{sec^2}{kg}}{100}$

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Total pressure drop in mbar : $dPtot = 2.129$

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