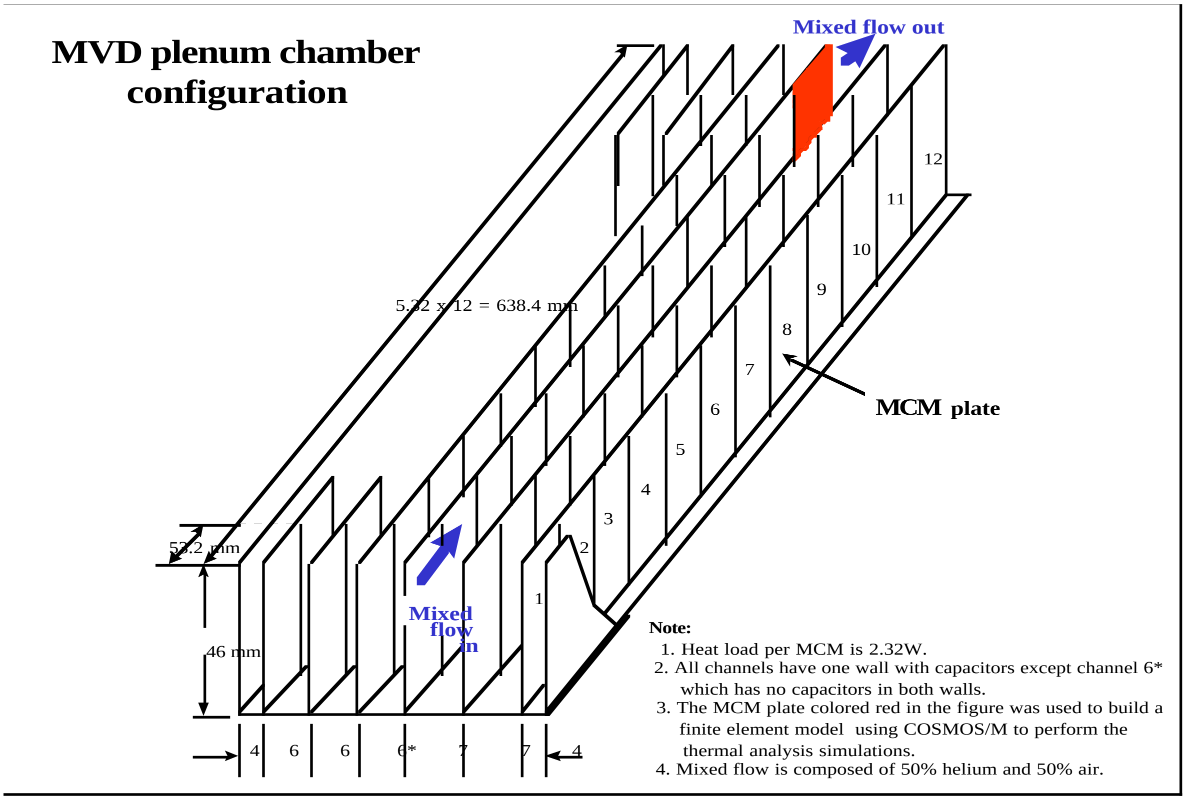
LANL-Memorandum
ESADE-97-004, Z. Chen, 10/10/96

ELECTRONICS COOLING FOR PHENIX MVD USING MIXED FLOW

I. INTRODUCTION

The simulation and calculation results of electronics cooling using air flow have been reported for the current design of the Phenix Multiplicity and Vertex Detector (MVD)[1]. It is known that using an air cooling system, with a turbulent airflow 9m/s of velocity, results in an average maximum temperature of 39.1^{0}C for the MCMs. However, the maximum temperature represented by the hot spots on the MCM is 40.7^{0}C which is a little higher than the design temperature requirement 40^{0}C. To maintain the MVD at optimized operational status , an evaluation using a mixed cooling flow composed of 50% helium and 50% air instead of 100% air cooling has been performed for the current MVD design.

The structure of the MVD was described in an earlier technical report [1]. The calculation and simulation in this report are based on the same plenum channels and the same MCM number as used in the earlier evaluation and is shown in Fig. 1. Another important factor for the heat transfer calculation is the heat load.



Note:
1. Heat load per MCM is 2.32W.
2. All channels have one wall with capacitors except channel 6* which has no capacitors in both walls.
3. The MCM plate colored red in the figure was used to build a finite element model using COSMOS/M to perform the thermal analysis simulations.
4. Mixed flow is composed of 50% helium and 50% air.

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Fig. 1: MVD plenum chamber configuration

We know that the main heat source in the system is the MCMs and each one dissipates about 2.32 w. A total heat load of the fully populated plenum channel used for the calculation is 27.84 w.

II. SOLUTION PROCEDURE

1. HEATING OF MIXED FLOW ALONG A CHANNEL IN THE FLOW DIRECTION

Assuming that the temperature is uniform across the channel cross section, the mixed flow temperature at some distance d from the inlet, T_{flow}, is equal to the mixed flow temperature at the inlet, T_{inlet}, plus a temperature increase corresponding to the heating of the mixed flow through the channel. Thus the helium and air mixed flow temperature is given by

$$T_{mixed\ flow} = T_{inlet} + Q/\rho\ \mathbf{v}\ A_c\ C_p\ , \qquad (1)$$

where Q is the total heat load from the inlet to d, assuming a uniform heat load distribution along the channel. The other variables in Eq. (1) are defined as

$Q = (2.32\ w)\ (12)(d/L)$,
L = total length of the channel = 53.2mm x 12=0.6384 m,
d = distance along the channel =53.2mm x MCM number,
ρ = the mixed flow density at room temperature (20^0C) = 0.680469 kg/m^3,
C_p = the mixed flow specific heat at 20^0C = 3100.248 W s/kg K,
v = the mixed flow velocity that needs to be determined in this study, and
A_c= the channel cross section.

In the current design it has been determined that the channel designated as 6* with 6mm spacing is the channel that we should use for the heat transfer evaluation since the combination of the cross section area and heat load will give the highest temperature in the MCM[1]. We can determine the maximum outlet temperature for several mixed flow velocities as shown in Fig. 2.

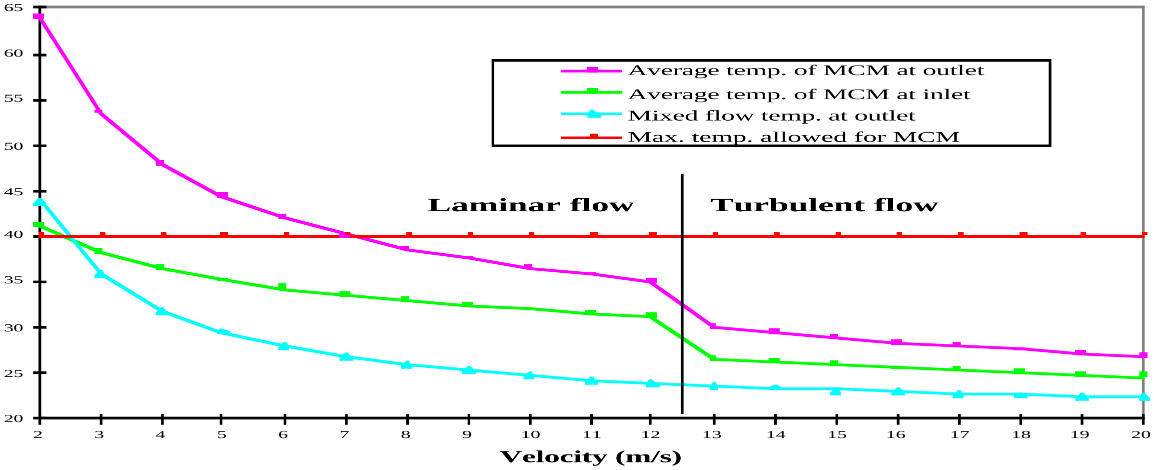


Fig. 2: **Average temperature reached by the MCMs located at the inlet and the outlet versus the mixed flow velocities in the channel with spacing 6* mm**

2. MCM-TO-MIXED FLOW THERMAL EXCHANGE

The average temperature of the MCM, T_{MCM}, is equal to the mixed flow temperature, $T_{mixed\ flow}$, plus a temperature differential from the exchange process between the cooling flow and the MCM plate. Thus, the average temperature reached by the MCM is

$$T_{MCM} = T_{mixed\ flow} + Q_{MCM} / h\ A_{MCM} \qquad (2)$$

where Q_{MCM} is the heat load dissipated by one side of the MCM and is assumed to be half of the heat load per MCM in the current design. The value of the variables in Eq (2) are

Q_{MCM} = 1.16 W,
A_{MCM} = the MCM surface area exposed to mixed flow = 2.4472×10^{-3} m^2, and
h = the heat transfer coefficient that depends on the flow regime (laminar or turbulent).
For a laminar flow, this coefficient is given by Sieder and Tate [2] as

$$h = 1.86\ (k/D_h)\ (Re\ Pr\ D_h/L)^{0.33}. \qquad (3)$$

For a fully developed turbulent flow, Dittus and Boelter [3] have given the following relation for h as

$$h = 0.023\ (k/D_h)\ (Re)^{0.8}(Pr)^{0.4}. \qquad (4)$$

In equations (3) and (4),

k = the mixed flow thermal conductivity at 20^0C = 8.7558×10^{-2} (W/m s K),
D_h = hydraulic diameter = $1.0615\text{x}10^{-2}$ (m^2) for the channel with spacing 6*mm,
= $1.2151\text{x}10^{-2}$ (m^2) for the channel with spacing 7mm, and
Pr = the Prandtl number for 50% helium and 50% air at room temperature = 0.694585.
The Reynolds number is given by the equation

$$Re = v\ D_h/\nu, \qquad (5)$$

where ν = the mixed flow kinematic viscosity at the room temperature (20^0C) = 6.64 $\text{x}10^{-5}$ m^2/s. The mixed flow character depends on the value of Reynolds number and for laminar flow, Re is less than 2000, otherwise, the flow is turbulent. As shown in Fig. 2, channel 6*, the flow condition will remain laminar until the velocity reaches 12.51 m/s. The average temperature reached by the MCM plate depends on the mixed flow velocity. From Fig. 2 it shows that if we use a velocity of 8m/s, the average temperature reached by the MCM plate will be lower than the cooling requirement of 40^0C. Considering the MCM heat spreading and safety margin, a velocity of 9m/s is chosen to compare with the results of airflow cooling, as shown in Fig. 3.

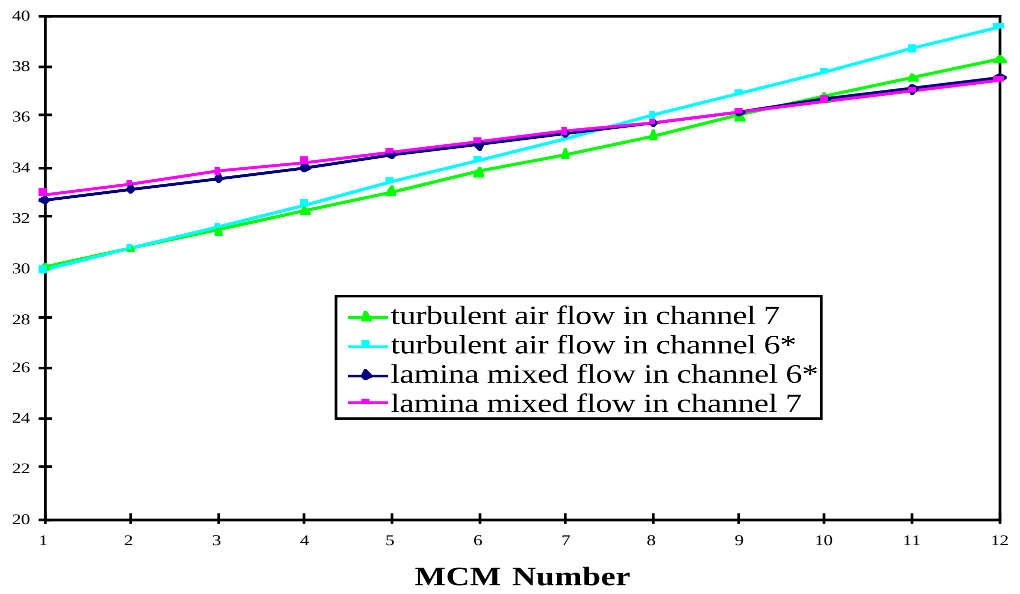


Fig. 3: Average temperature reached by the MCMs for the 12 modules comparing the turbulent air flow and laminar mixed flow with the same velocity of 9 m/s

As shown in Fig. 2, at any given mixed flow velocity, the average temperature reached by the MCM plates is a function of the mixed flow temperature along the channel. The temperature differential for the MCM-to-flow thermal exchange is constant and is given by Q_{MCM} / h A_{MCM}. Therefore, for a given mixed flow velocity, the MCM temperature is a linear function of the distance from the inlet. The MCM plate that is located at the outlet is the least cooled since the flow temperature is the warmest there. In Fig. 3, it is shown that with the same flow velocity, using 50% helium and 50% air flow to cool the MCMs, the slope of the temperature curve reached by MCMs along the flow direction and within the same channel gives a smaller slope than the one where 100% air is used to cool down the MCMs.

The mixed flow velocity of 9m/s in the channel 6* produces an average heat transfer coefficient of 38.79 W/m^2 ^{0}C and the outlet air temperature in this channel will reach 25.31^{0}C. To determine the MCM plate which is cooled least and therefore represents the maximum temperature reached by the MCMs, an evaluation has also been done for a channel spacing of 7mm that uses an effective spacing of 6.52mm. With a mixed flow velocity of 9m/s, an average heat transfer coefficient of 37.83 W/m^2 ^{0}C is produced in this channel and the outlet mixed flow temperature is 24.89^{0}C.

The spreadsheets used for the above calculations are attached in Appendix 1, 2 and 3.

3. MCM HEAT SPREADING

All parameters of a MCM and the heat generated by silicon chips are the same as reported and shown in Fig. 2 of the earlier technical report[1].

Using COSMOS/M HSTAR for the heat transfer analysis, a finite element model of a typical MCM plate (the one with the red color as shown in Fig. 1) was created to simulate a 9m/s airflow and convective heat transfer on both sides of this plate. The same finite element model that was used for the 100% airflow cooling was performed for simulation with mixed flow to cool the MCMs. As described in section 2 of the solution procedure, one side of this MCM plate faces channel 6*, where the ambient air temperature was set to a computed outlet air temperature of 25.31^0C. The average heat transfer coefficient was set to 38.79×10^{-6} W/mm^2 ^{0}C, which corresponds to a 9m/s mixed flow for this channel. On the other side of this MCM plate is channel 7, and from the computed results, the ambient air temperature was set to 24.89^0C. The average heat transfer coefficient was set to 37.82×10^{-6} W/mm^2 ^{0}C.

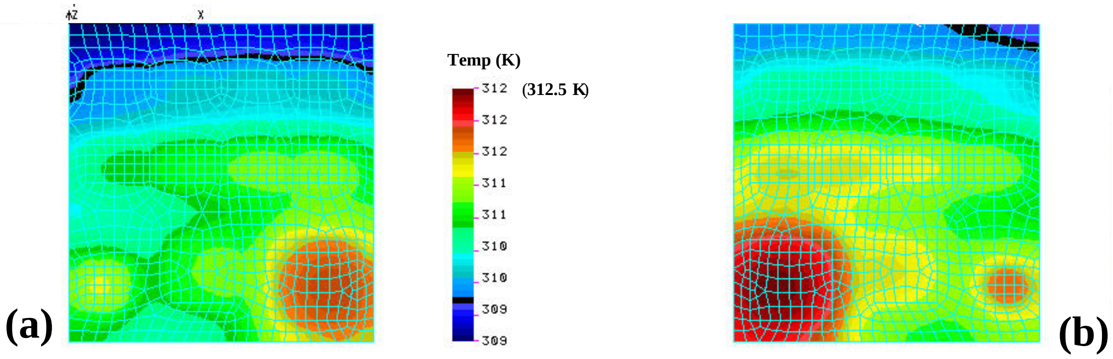
In addition to the ambient mixed flow temperature and the average heat transfer coefficients, the boundary conditions for this model also include the volumetric energy dissipated from the chips. They are:

- in the first row, the volumetric energy dissipated by the chips: 8.696×10^{-3} W/mm^3
- in the second row, the volumetric energy dissipated by the chips: 7.681×10^{-3} W/mm^3
- in the third row, the volumetric energy dissipated by the left chip: 1.422×10^{-2} W/mm^3
- in the third row , the volumetric energy dissipated by the central chip: 5.331×10^{-3} W/mm^3
- in the third row , the volumetric energy dissipated by the right chip: 6.300×10^{-3} W/mm^3

The finite element analysis was performed for a model which contains 3 layers of material with different thermal conductivities. The first layer facing channel 6* is pure alumina substrate, 1.0mm in thickness with a thermal conductivity of 29.427×10^{-3} W/mm K. The second layer, middle one, is 0.5 mm in thickness, contains alumina substrate, and all silicon chips have a thermal conductivity of 148×10^{-3} W/mm K. The third layer facing the channel with 7mm spacing is the kapton cover which is made of four mini layers and the total thickness is 0.2mm with a thermal conductivity of 0.2×10^{-3} W/mm K. The unit system of the analysis used is w, k, mm.

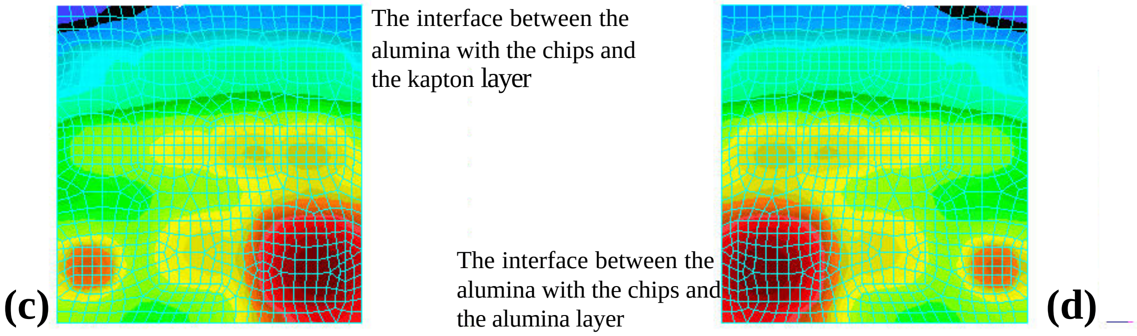
The thermal analysis for the MCM plate using the mixed flow cooling was carried out to determine the temperature distribution and heat flux contours which will identify hot spot locations.

The temperature contours of the kapton surface and the alumina surface are shown in Fig. 4(a) and (b), respectively. To find the hottest spots in the electronic system for the MVD, the nodes that are the hot spots and represent the maximum temperature on the MCM plate have been found on both sides of the alumina containing the silicon chips that are plotted and are shown in Fig. 4 (c) and (d). The average temperature on the MCM plate is 310.7^0K (37.7^0C), which agrees well with the 37.5^0C calculated by hand as shown in Appendix 2 and 3. The maximum temperature on the MCM plate which is represented by the hot spots is 312.43^0K (39.43^0C) that is 0.6^0C lower than the maximum temperature reached by the MCM in the design requirement and it is 1.9^0C higher than the average maximum temperature reached by the MCM. The total temperature difference across the entire plate is 3.4^0C. The maximum hot spot is located in the central part of the biggest chip. This is not surprising since the high volumetric energy is dissipated into a big volume that is closely surrounded by additional energy dissipaters. The smaller chip in the third row left which dissipates the highest volumetric energy, has no hot spot and is cooler than the right one. This is because this chip is not close to the other chips and its small volume allows the heat to be dissipated easily to the environment.



Kapton surface

Alumina surface

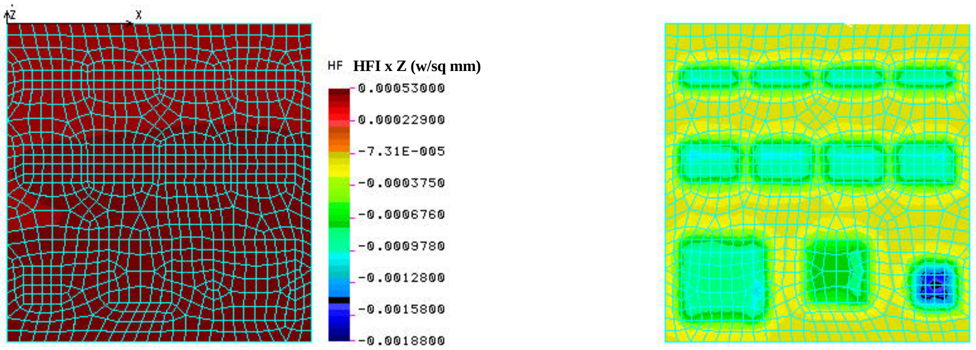


The interface between the alumina with the chips and the kapton layer

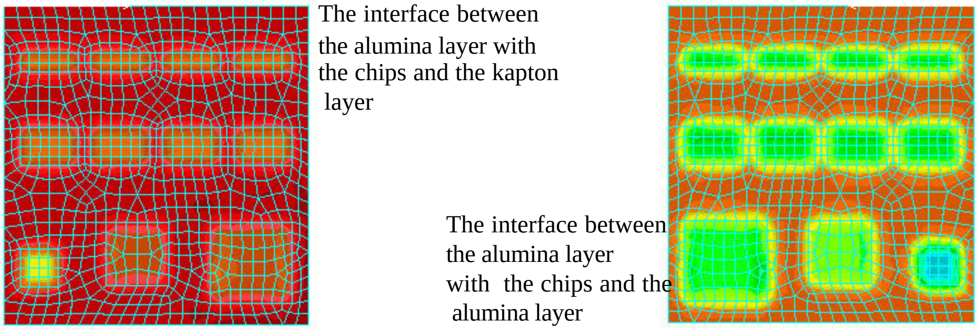
The interface between the alumina with the chips and the alumina layer

Fig. 4: Temperature distribution for the MCM current design with cooling flow of 50% Helium and 50% Air. Contour (a) is for the kapton surface; Contour (b) shows the Alumina surface; Contour (c) is located at the interface of alumina layer containing the chips and the kapton layer; Contour (d) is located at the interface of alumina layer containing the chips and the pure alumina layer.

Heat flux contours are shown in Fig. 5 and describe the magnitude and direction of the heat flux. On the legend, the positive heat flux is the heat flux to the kapton surface and the negative heat flux is to the alumina surface. The heat flux distribution is similar to the temperature distribution since the value of the heat flux is equal to the temperature difference between the mixed flow and the MCM plate multiplied by the average thermal coefficient which depends on the thermal conductivity of the material. This explains why the heat flux is larger toward the alumina than to the kapton. Fig. 5 (a) shows the heat flux contour on the kapton surface where the area in dark red (HF about 5.3×10^{-4} W/mm^2) indicates where the temperature is higher and the hot spots are located. But on the alumina surface as shown in Fig. 5 (b), the higher heat flux (about 10×10^{-4} -18.8×10^{-4} W/mm^2) is blue and dark blue in color and are in the higher temperature area. The dark yellow color area is where little heat is dissipated by the silicon chips and the lower heat flux results in a lower temperature.



(a) **Kapton surface** **Alumina surface** **(b)**



The interface between the alumina layer with the chips and the kapton layer

The interface between the alumina layer with the chips and the alumina layer

(c) **(d)**

Fig. 5: Heat flux contours for the MCM current design with cooling flow of 50% Helium and 50% Air. Contour (a) is for the kapton surface. Contour (b) shows the heat flux on the alumina surface. Contour (c) is located at the interface of the alumina layer containing the chips and kapton layer. Contour (d) is located at the interface of the alumina layer containing the chips and alumina layer.

Figure 6 shows a summary of the heat transfer phenomena for the MCM plate.

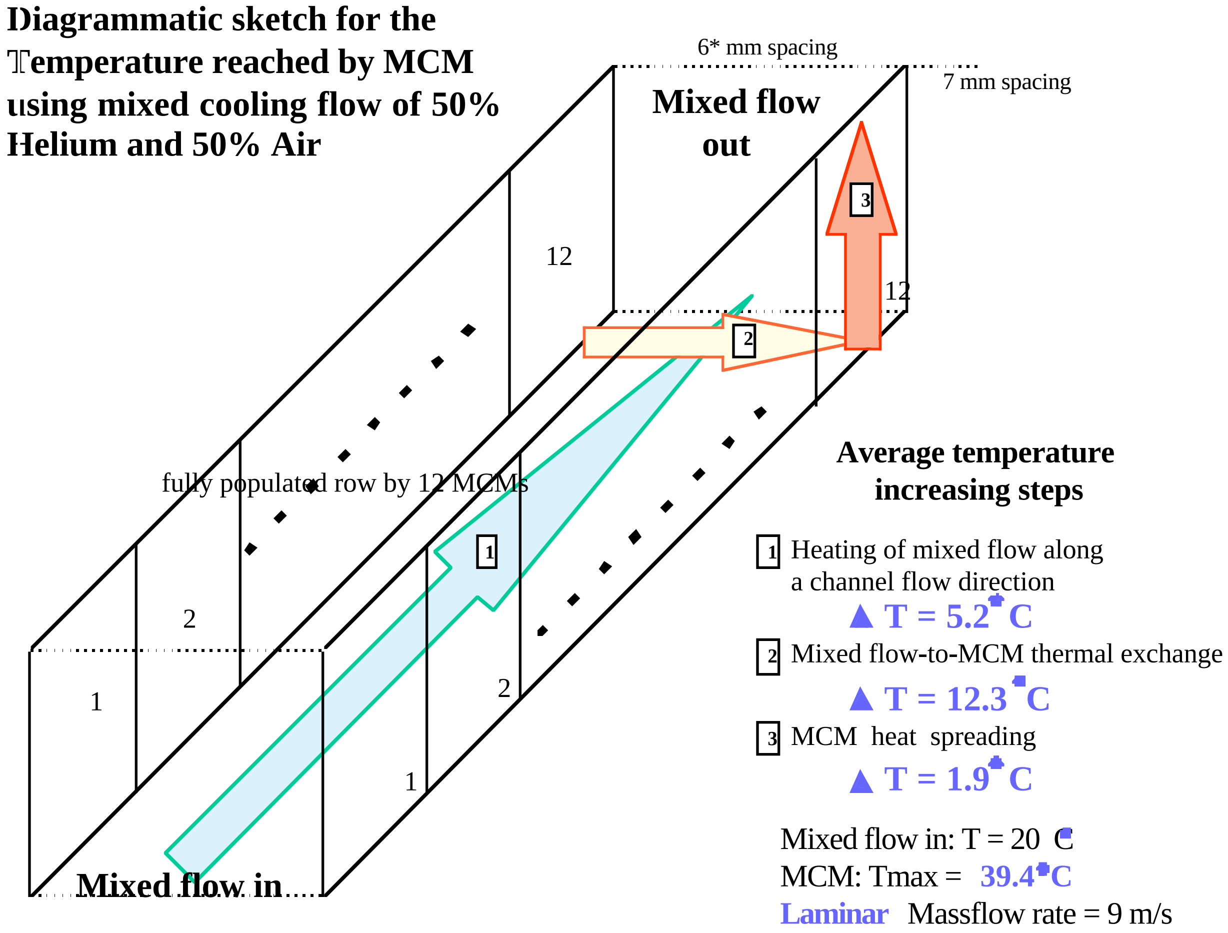


Fig. 6: Diagrammatic sketch for the Temperature reached by the MCM using cooling flow of 50% helium and 50% air

III. SUMMARY

The new MCM design using 50% helium and 50% air cooling flow has been analyzed for cooling effectiveness. For the current MCM design, using a cooling system with a velocity of 9m/s and laminar flow, the average maximum temperature reached by the MCMs is 37.5^{0}C. The maximum temperature which is represented by the hot spots on the MCM is 39.43^{0}C which well meets the design temperature requirement 40^{0}C.

To understand the electronics cooling using an airflow or a mixed flow of helium and air for the current MCM design, a comparison has been done and is listed in Table 1. When using the same flow velocity of 9m/s to cool the MCMs, the helium and air mixed is a laminar flow while airflow is turbulent. The mixed flow will

provide better cooling results than the airflow. However, to achieve the same cooling effectiveness, using mixed flow may cost more than using airflow.

Table 1: Comparison on Airflow and Helium/Air mixed flow for cooling MVD

COMPARISONS	**unit**	**Airflow**		**Mixed flow** (0.5 He + 0.5 air)	
FLOW PROPERTIES		**Channel6 ***	**Channel 7**	**Channel6 ***	**Channel 7**
Kinematic viscosity (20C)	nu (m^2/s)	1.53E-5	1.53E-5	6.64E-5	6.64E-5
Thermal conductivity (20C)	k (w/msk)	2.574E-2	2.574E-2	8.756E-2	8.756E-2
Density (20C)	rho(kg/m^3)	1.1941	1.1941	0.6805	0.6805
Specific heat (20C)	Cp(ws/kgk)	1007.08	1007.08	3100.25	3100.25
SAME PARAMETERS					
Total heat load of each MCM	Q (w)	2.32	2.32	2.32	2.32
Total heat load of the channel	Q (w)	27.84	27.84	27.84	27.84
MCM length	l (m)	5.32E-02	5.32E-02	5.32E-02	5.32E-02
MCM width	w (m)	4.60E-02	4.60E-02	4.60E-02	4.60E-02
Thickness	t (m)	1.70E-02	1.70E-02	1.70E-02	1.70E-02
Plenum length (12*l)	L (m)	0.6348	0.6348	0.6348	0.6348
Heat area of plenum	Ah (m^2)	5.873E-02	5.873E-02	5.873E-02	5.873E-02
Flow temp. at inlet	t1 (k)	293	293	293	293
Spacing between 2 MCMs	s (m)	6.00E-03	6.52E-03	6.00E-03	6.52E-03
Hydraulic diameter	Dh (m)	1.0615E-2	1.2151E-2	1.0615E-2	1.2151E-2
Flow velocity determined	v (m/s)	9	9	9	9
DIFFERENT PARAMETER					
Reynolds number	Re	6271	7178	1439	1548
Flow state		**Turbulent**	**Turbulent**	**Laminar**	**Laminar**
Prandtl number (20C)	Pr	0.72	0.72	0.694585	0.694585
Nusselt number	Nud	22.00	24.52	4.7022	4.9349
Average heat transfer coeff.	h (w/m^2 k)	52.72	51.32	38.79	37.83
RESULTS					
Max. flow temp. at outlet	t2 (K)/(C)	303.6/30.6	302.0/29.0	298.3/25.3	297.9/24.9
Max. temp reached by MCM	t3 (k)/(C)	312.5/39.5	311.3/38.3	310.5/37.5	310.4/37.4

Temp of hot spot on MCM	t4 (C)	40.7	40.7	39.4	39.4
COST need be determined	**$**	**?**		**?**	

REFERENCES

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