



## NUMERICAL INVESTIGATION OF MHD FLOW IN COMBINED ATTITUDE AND THERMAL CONTROL SYSTEM

Junxian Chew and Renuganth Varatharajoo

Department of Aerospace Engineering, Universiti Putra Malaysia, Malaysia

E-Mail: [chewjunxian@gmail.com](mailto:chewjunxian@gmail.com)

### ABSTRACT

Combined Attitude and Thermal Control System (CATCS) was proposed for the implementation of an integrated solution for the satellite thermal and attitude control. This paper focuses on the CATCS numerical simulation of the Magnetohydrodynamic (MHD) driven flow of liquid metal within its channel. The numerical solution to the core mean velocity of liquid flowing through CATCS duct is obtained through the coupling of electric and magnetic fields towards an integrated solution in describing the MHD flow. The conventional Navier-Stokes equation is modified using Reynolds Averaging, yielding Reynolds Averaged Navier-Stokes (RANS) equation to solve the respective flow profile. Additional constraint is placed upon the flow in consideration of Hartmann layer effects. Simulation is also performed based on the variation of injected magnetic flux densities and induced thermoelectric currents to yield for different magnitudes of Lorentz forces that drive the liquid. Results show that the core mean velocity is mainly governed by the injected currents; whereas the flow profile shape is governed mainly by the magnetic fields.

**Keywords:** CATCS, MHD, magnetic flux density, thermoelectric.

### INTRODUCTION

Magnetohydrodynamic flow in this study mainly concerns the formation of Hartmann Layer and its effect on the development of fluid flow profile within the Combined Attitude and Thermal Control System (CATCS) aboard a satellite. The nature and formation of Hartmann Layers are understood and discussed by Moreau (1990) [1]. It is well understood at this point that Hartmann Layer acts as the channel for electric currents which has a huge influence on the velocity profile of the conducting fluid. Formation of Hartmann Layer can be interpreted as the effect of Hartmann Braking. It results from the magnetic field lines that are not aligned with the wall of the duct thus causing a resistance in the general flow direction.

Instead of treating the problem in 3D perturbation flow regime, it is found and mentioned by Sommeria and Moreau [2] that the flow develops multiple characteristics of 2D turbulence in rectangular insulating ducts immersed in a strong transverse magnetic field. Further study by Moresco and Alboussière [3] indicates that the formation of 2D turbulence characteristics is dependent mainly on Hartmann number and Reynold numbers  $Ha/Re$ . Further inspection indicates that  $Ha$  is dependent on the strength of Magnetic Fields  $B$ . Following such developments, it is noted that the transition from three dimensional turbulence to 2D turbulence is more prominent as the magnetic field strength increases.

With such a phenomenon observed, the term “quasi 2D” is used to describe simplifying approximation of the originally 3D perturbation into strictly a 2D MHD turbulence. The effect of Hartmann Layer and the formation of Quasi-2D turbulent flows are well documented by Messadek and Moreau [4] using an experimental setup involving a circular cylinder of vertical axis with radius of 0.11m and a depth of 0.01m. Transverse magnetic field is imposed onto the cylinder;

and the electric field is created through the use of small electrodes inserted into the bottom plate of the cylinder, with both being perpendicular to each other.

Since the work of Messadek and Moreau [4] is entirely experimental, Smolentsev worked with Moreau [5] and proposed a set of zero and one equation turbulence model to simulate the fluid flow profile within Messadek and Moreau’s experimental setup.

Although the nature of the fluid flow under those conditions is well explored and understood, none have tried to simulate similar conditions aboard the CATCS. Varatharajoo and Fasoulas [6] had proposed and designed the combination of two systems of attitude control and thermal control. It would effectively provide innovative synergistic systems that improves the satellite operations [7, 8]. A circular duct is used to carry conducting liquid that provides momentum, and at the same time transports heat to be radiated outwards. The duct dimension is comparatively small from Messadek and Moreau [4] experiment setup, with 0.005m width and a height of 0.02m. Before the system is implemented, the suitability of such a MHD driven mechanism had to be qualitatively analysed especially in terms of its fluid flows.

The present study will employ the use of COMSOL Multiphysic in order to simulate the integration of multiple fields, namely fluid dynamics and electromagnetics. Simulation for the development of turbulence flow uses Reynolds’ Averaged Navier Stokes equations to provide a time averaged solution to the modeling. Smolentsev and Moreau’s [5] zero equation turbulence model is used to simulate the development of the Quasi 2D turbulence within the duct flow. This maiden work will provide the evidence of MHD flows within the CATCS ducts whereby a minimum flow of 0.01 m/s is needed for the CATCS operation [9].



## METHODOLOGY

### Turbulence modeling

Following the assertion made by Messadek and Moreau [4], the core mean velocity of the developed quasi 2D turbulence flow is given below:

$$U_{\theta}(r, t) = \frac{I}{4\pi r \sqrt{\sigma \rho \nu}} \left( 1 - \exp\left(-\frac{\nu Ha}{h^2} t\right) \right) \quad (1)$$

It is noted that the main variables that affect the resultant core mean velocity is the Hartmann number  $Ha$  and electric current. Hartmann number  $Ha$ , on the other hand is defined as below:

$$Ha = \sqrt{\frac{\sigma}{\rho \nu}} B_0 h \quad (2)$$

As shown in equation (1), Messadek and Moreau had already asserted that the core mean velocity is already a strictly 2D problem as  $U_{\theta}$  is bounded by  $r(x, y)$  and  $t$ .

Sommeria and Moreau had already detailed a Reynolds' averaged Navier Stokes equation for use to simulate the resulting flow profile, and included a volume force term that describes the effect of the Hartmann Braking (subsequently formation of Hartmann Layer near duct wall), as shown below:

$$\frac{dV}{dt} = \frac{1}{\rho} \nabla P + \nu \nabla^2 V - \frac{U_{\theta}}{t_H} \quad (3)$$

Solve  $V$  in order to determine the resulting velocity profile.  $t_H$  is defined as the timescale for the Hartmann braking effect defined as below by Smolentsev [5], shown below:

$$t_H = \frac{b^2}{\nu \times Ha} \quad (4)$$

Following Smolentsev's formulation for the zero equation model, turbulence kinetic energy and its dissipation rate does not have to be predefined. To achieve a closure of the problem, the turbulence viscosity had to be defined explicitly as shown below:

$$\nu_t = 0.25 \delta^2 / t_H \quad (5)$$

$\delta$  is the Hartmann shear layer thickness defined by Messadek and Moreau [4] is shown to

$$\delta \approx h \cdot \left( \frac{Ha}{Re} \right)^{\frac{1}{2}} \quad (6)$$

Reynolds' number is further defined by Smolentsev as shown below:

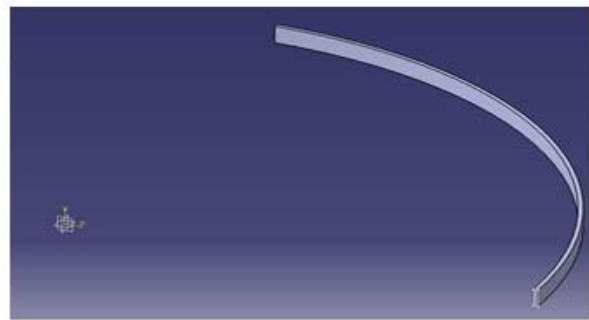
$$Re = U_0 L / \nu \quad (7)$$

where  $U_0$  is the initial velocity  $L$  is the duct cross-sectional dimension. No slip condition had been applied to all the CATCS duct's bounding walls and all the bounding walls are considered to be insulating. The conservation of electric current density is achieved, thus Hartmann braking occurs near the wall and the influence of viscosity is transmitted into the core flow.

Turbulence simulation is then performed by first modifying the provided RANS equation found in COMSOL Multiphysics' Turbulence Flow module. It is done to incorporate all the above formulations into the set of equations of which the simulation will base itself on.

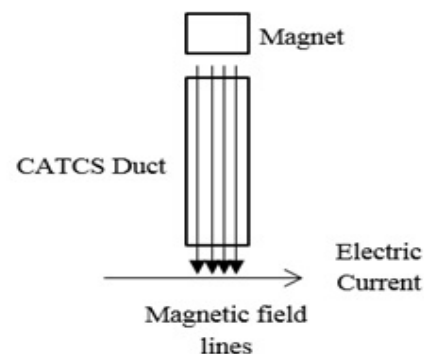
### Simulation model setup

A full CATCS setup description is given in Ref. [2]. Only a quarter section of the CATCS duct is modelled herein as it is a circular and a symmetric duct. Figure-1 shows the duct as being modelled in CATIA. The duct is a circular construct with a radius of 0.5m.



**Figure-1.** CATCS Duct, 0.005m width × 0.02m height.

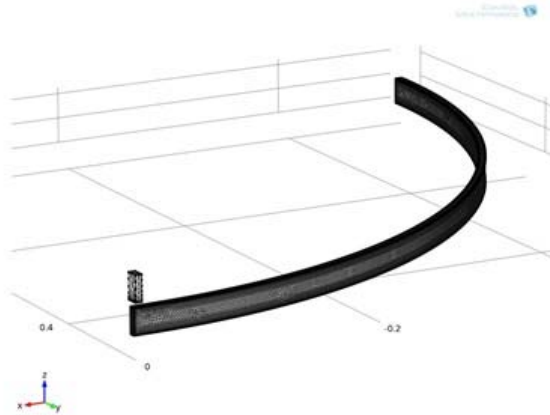
A total of four permanent magnets will be placed at regular intervals above the duct, thus creating a magnetic field which is aligned vertically downwards. Electric current is passed through the bottom plate, generated from the thermoelectric material due to the temperature gradient between the inner construct of satellite and its outer wall. Hence both the electric and magnetic fields are aligned perpendicular to each other. Figure-2 clearly illustrates the field lines for both magnet and the electric fields.



**Figure-2.** Cross section of CATCS duct.



For the current study, magnetic field lines are directly imposed onto the conducting fluid to simulate a constant magnetic flux density throughout the duct.



**Figure-3.** Meshed CATCS duct with permanent magnet.

Figure-3 shows the meshed duct that is used for the fluid flow simulation. Mesh density is controlled to concentrate on the duct domain and in regions close to the bounding duct walls.

There are two main variables that this study focuses on, which are the electric current and the magnetic flux density. Variations are made to the above variables to understand the effects both have on the resultant fluid flow profile.

## RESULTS

Ten study cases were carried out, with two variants on the electric current (at 40A and 80A) and five variants for the magnetic flux densities (0.5T, 1T, 2T, 5T, 10T). Table 1 shows the effects of varying the magnetic flux density on the core mean velocity of the conducting fluid. It is clear that the stronger the magnetic field gets, the faster the fluid flows. However, there is a limit to its increase in speed. It is seen that the velocity reaches its maximum around 5T of magnetic flux density, and increasing it to 10T does not contribute much in the overall velocity increment. Even though the effects of magnetic flux densities diminish as the magnitude increases, it has a great impact on the development and formation of quasi 2D turbulence flow.

Figure-4 clearly shows that the fluid flow develops quasi 2D properties a lot faster as the magnetic flux density increases. The region of high turbulence quickly smooths itself for case B compared to case A. It further confirms the fact that the transition from 3D turbulence to quasi 2D is facilitated by the strength of magnetic flux densities.

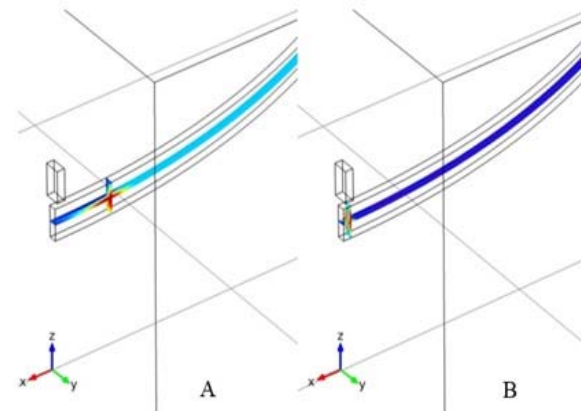
Results from Table-1 clearly shows that the core mean velocity is highly dependent on the electric current passing through the fluid. Direct comparison of the velocity magnitude shows that as the electric current doubles, the core mean velocity doubles as a result. At the

same time, core mean velocity gain under the effect of magnetic field flat lined around 5T and 10.

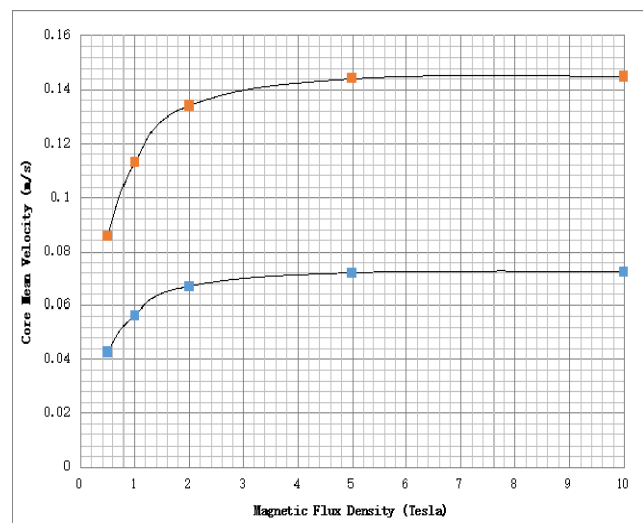
**Table-1.** Summary of difference in Core mean velocity (m/s) for both 40A and 80A cases.

Magnetic Flux Density (T)	Core Mean Velocity (m/s)	
	40A	80A
0.5	0.0426	0.0854
1	0.0564	0.1130
2	0.0670	0.1340
5	0.0721	0.1443
10	0.0725	0.1450

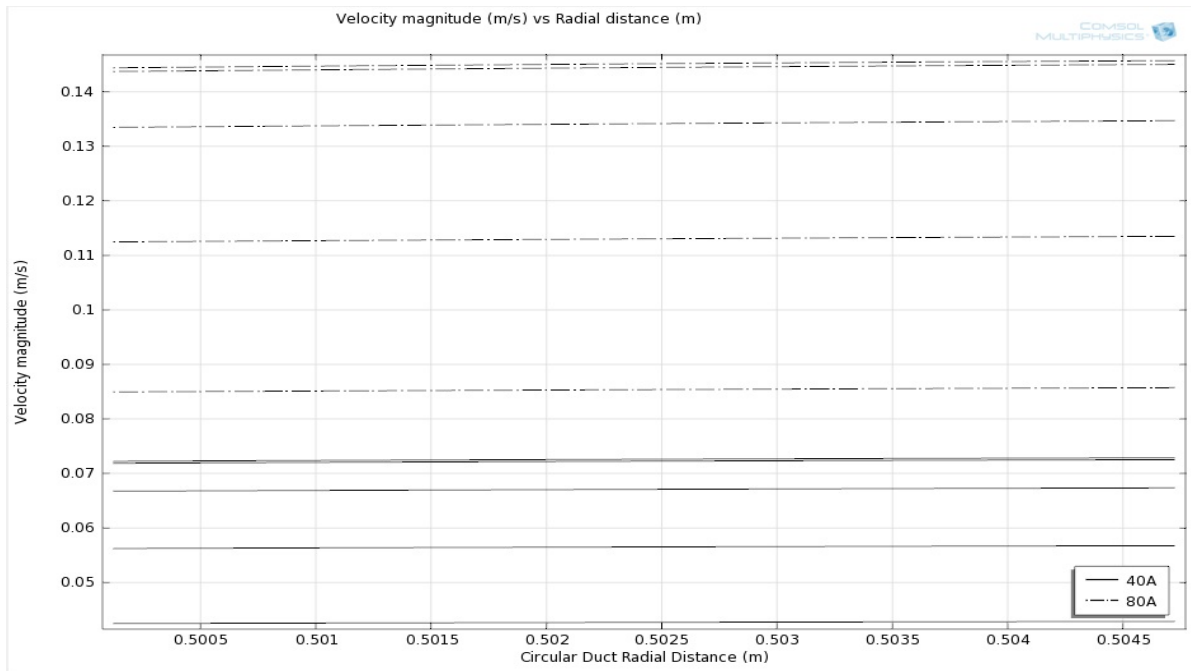
Plotting the above data into Figure-5 shows the effect of both electric current and magnetic flux density on the fluid's core mean velocity.



**Figure-4.** Comparison of flow profile for two cases: A)  $I = 40A, 0.5T$  and B)  $I = 40A, 10T$ .

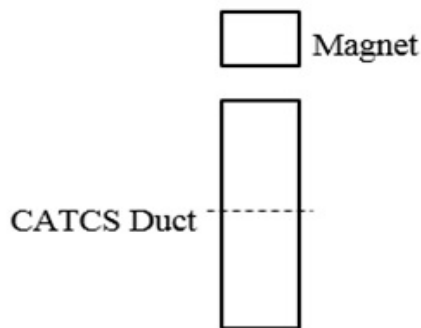


**Figure-5.** Core mean velocity vs magnetic flux density.



**Figure-6.** Velocity magnitude of fluid along the transverse cross sectional line (circular duct radial direction).

Figure-6 displays horizontal velocity distribution measured across the duct cross section, shown in Figure-7. It is clear that the fluid flow had reached an almost uniform profile. There exists only slight increase of velocity at the outer wall compared to the inner wall. There are a total of ten lines; each corresponds to the ten study cases performed. Two distinct groups can be observed, one for 40A and the other for 80A test cases.

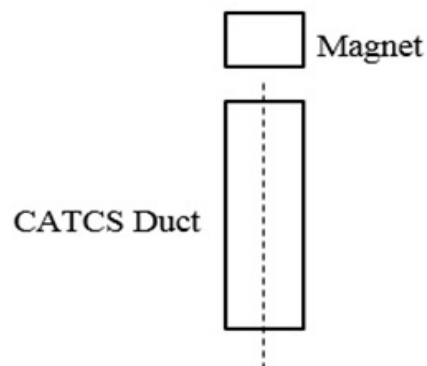


**Figure-7.** Location line at which velocity distribution is measured and graphed.

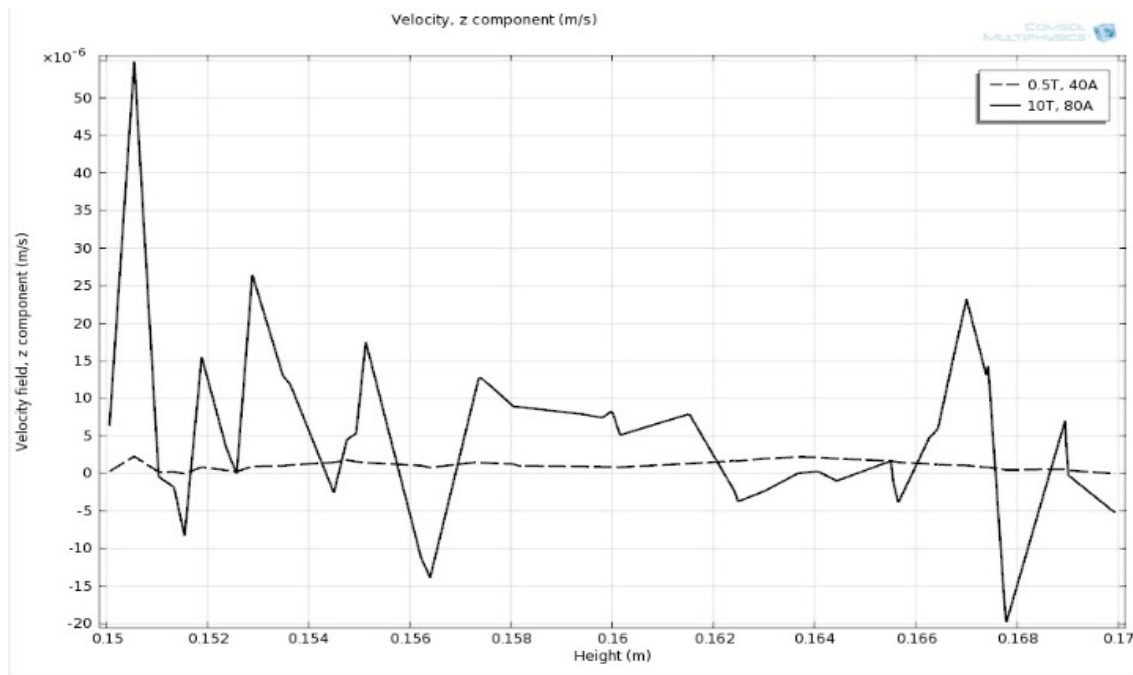
Figure-9 further confirms that the fluid flow exhibits a quasi 2D turbulence profile. Note that the graph is drawn at the velocity magnitude in the order of  $10^{-6}$  along the location line shown in Figure-8. The two lines are the comparisons of two extremes of the test cases performed. Even at the highest range of magnetic flux density and electric current, the  $z$  - velocity component only peaks at about  $55 \times 10^{-6}$  m/s. The variations are not much, thus signifying the turbulence happens mainly on  $x$  and  $y$  axes.

## CONCLUSIONS

The study of MHD flow within the CATCS duct shows that the resulting fluid flow profile has some similarity in observed phenomenon compared to the reported experimental results. The quasi 2D turbulence is observed within the MHD flow of CATCS duct and it forms a uniform velocity profile once the fluid flow fully develops. It also confirmed that the main variable that controls the velocity magnitude of the resulting flow is the amount of electric current injected into the fluid, while the magnetic field helps the formation of quasi 2D turbulence characteristics. Therefore, this work provides the evidence that the fluid flow within the CATCS duct is indeed sufficient ( $> 0.01$  m/s) to provide the required fluid velocity for its operation.



**Figure-8.** Location line at which  $z$ -velocity component is measured.



**Figure-9.** Velocity of z-component of fluid flow.

## REFERENCES

- [1] Moreau R. 1990. *Magnetohydrodynamics*. 1<sup>st</sup> Ed. Kluwer Academic Publishers. Dordrecht. p. 1.
- [2] Sommeria J. and Moreau R. 1982. Why, How and When, MHD Turbulence Becomes Two-Dimensional. *Journal of Fluid Mechanics*. Vol. 118, p. 507.
- [3] Moresco P. and Alboussi re T. 2003. Experimental Studies on the Instability of the Hartmann Layer. *Journal of Fluid Mechanics*, 504. pp. 167-181.
- [4] Messadek K. and Moreau R. 2002. An Experimental Investigation of MHD Quasi-2D Turbulent Shear Flows. *Journal of Fluid Mechanics*. Vol. 426. pp. 137-159.
- [5] Smolentsev S. and Moreau R. 2006. Modelling Quasi-Two-Dimensional Turbulence in MHD Duct Flows. *Proceedings for Summer Program*, p. 419.
- [6] Varatharajoo R., Kahle R. and Fasoulas S. 2003. Approach for Combining Attitude and Thermal Control Systems. *Journal of Spacecraft and Rockets*, AIAA, Vol. 40, pp. 657-664.
- [7] Varatharajoo R. 2006. Onboard Errors of the Combined Energy and Attitude Control System, *Acta Astronautica*, Vol. 58, No. 11, pp. 561-563.
- [8] Stoll E., Jaekel S., Katz J., Saenz-Otero A., Varatharajoo R. 2011. SPHERES Interact - Human-Machine Interaction Aboard the International Space Station. *Journal of Field Robotics*, Vol. 29, No. 4, pp. 554-575.
- [9] Khodari S. B., Renuganth V. 2009. H<sub>2</sub> and H<sub>∞</sub> Control Options for the Combined Attitude and Thermal Control System (CATCS), *Advances in Space Research*, Vol. 43, No. 12, pp. 1897-1903.