CFD simulation of nuclear aerosol containment systems

George Pichurov, Detelin Markov, Alexander Wolski, Emil Ivanov, Petar Bakardjhiev

***Abstract**: The paper presents numerical simulation of the natural cooling capacity of filter aerosol systems used in severe accident containment scenarios. Verification experiment was carried out to compare filter temperatures and flow velocities. The task comprised a typical natural convection study in a double cavity domain. The radiation heat transfer was modeled by the Discrete Ordinates radiation model. The surface emissivity had to be corrected in order to match numerical with experimental data. Rayleigh number calculation determined the flow as transitional, therefore laminar and turbulent flow simulations were done.*

***Key words:** Aerosol filters, natural convection, CFD*

INTRODUCTION

The Fukushima's accident has led many countries to consider the implementation of Filtered Containment Venting Systems (FCVSs) on Nuclear Power Plants (NPP). One of the possible design solutions is the use of an array of HEPA filters intermixed with cooling pipes in a filter assembly module. The filters capture the radioactive particles from nuclear fallout and are in turn heated by their radioactive decay. The design goal is to minimize the filter temperatures to prevent their meltdown and contamination escape into the atmosphere. This should be achieved at the absence of mechanical means of cooling. A test assembly with electrically heated filters was experimentally studied to verify the numerical methods employed. Detailed description of the device can be found in [1].

TEST ASSEMBLY

The test assembly unit is composed of a vertical cylinder case with three vertical HEPA filters and four vertical cooling pipes, Figure 1..

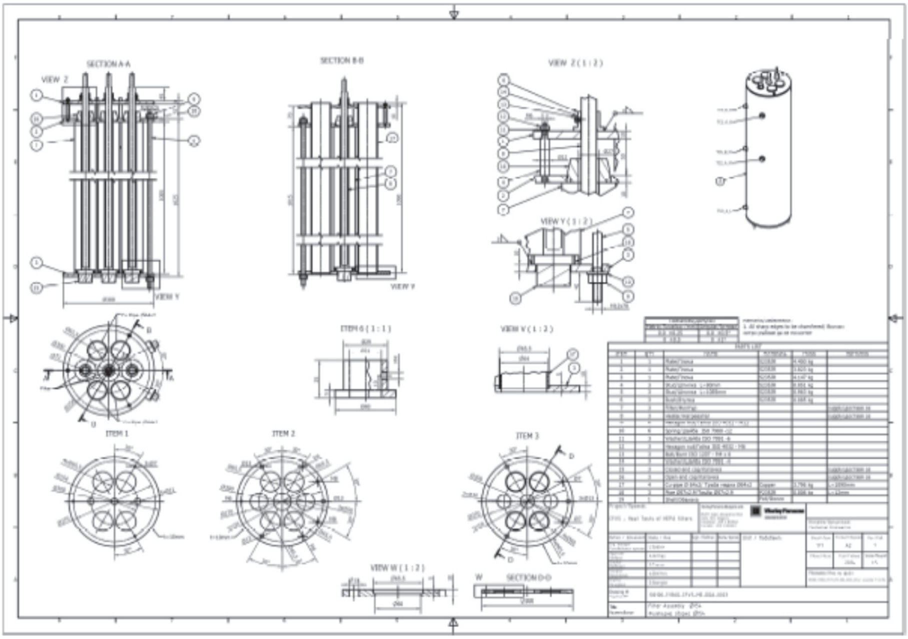


Figure 1 Test unit drawing

The case is with a diameter of 310 mm and height of 1100 mm. The parts of the assembly and their most important properties used in the numerical simulation are summarized in **Error! Not a valid bookmark self-reference.**

Table 1 Test assembly material properties

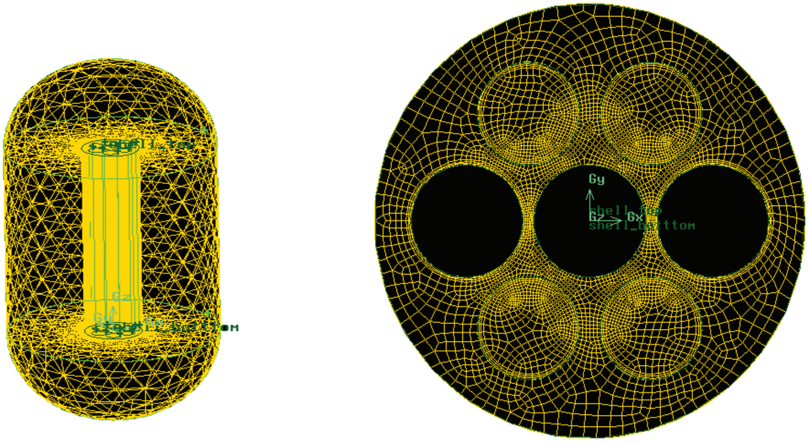
Part		Material	Thickness [mm]	Emissivity
Case plates		S235JR steel	10	0.91
Filters		SS316 steel	1 (used for thermal conductivity calculations only)	0.91
Pipes		Copper	2	0.95 (updated to 0.07 for roughly polished pipes)
Case shell	inside	Perforated aluminum sheet	3	0.70
	outside	Aluminum foil	0.1	0.03

The filters are heated with 322W each for a total rate of 966W while the temperature of the surrounding walls was 19°C.

NUMERICAL SIMULATION

Incompressible ideal gas model with polynomials of third order for the viscosity, specific heat and thermal conductivity of air were used. Conjugated heat transfer was modeled by enabling heat conduction within the metallic walls of the assembly, including three-dimensional heat conduction for some of them. *Figure 2* shows the geometry and mesh of the computational domain together with the filter assembly test unit. Later it was discovered that the domain size was not sufficient to ensure correct heat dissipation therefore a model of the real chamber was constructed with dimensions 10x5x3.5m, which is partly shown on *Figure 3*. There are no inlets and outlets into the domain, thus it is a closed cavity. The only driving force in this case comes from buoyancy due to air heating. The planar bases of the filter assembly cylinder were meshed with a sizing function of the "proximity" type which imposes certain restrictions on the mesh, like minimum number of cells between edges that comprise the surface (in this case the edges of the filters and cooling pipes). That is why the mesh is finer between the pipes and filters and is coarsened away from them. This is done automatically by the sizing function after specifying a minimum number of cell layers between edges and the cell growth rate. Inside the size function mesh a boundary layer mesh was incorporated encircling the filters and migrating inside the cooling pipes (Figure 2b). This allows for better resolution of boundary effects like heat transfer. During mesh creation, the boundary layer mesh is prioritized so that it is not impacted by the size function. The final surface mesh is extruded along the axis of the filter assembly to create a 3D hexagonal mesh inside the assembly volume, which generates more efficient cell pattern than the alternative tetrahedral mesh. A boundary layer mesh is also extended around the external wall of the filter assembly, which morphs into a tetrahedral mesh in the rest of the computational domain (*Figure 3*). Due to the large domain, nearly 1 million cells were needed to achieve a satisfactory mesh quality with sufficient detail.

Seventeen major cases were simulated with variants thereof. The first case comprises the initial bubble-like domain in a laminar flow. Then the domain was extended to cover the real experimental conditions and a necessary inclusion to the test unit geometry was added, namely a missing plate below the top of the unit. It was decided to study the effect of shell conduction for different set of surfaces: pipe conduction only, pipe and (base) plates conduction, filter and pipes conduction, and all three surface conduction enabled (filters, pipes and plates), which resulted in four cases. Then it was decided to study the possible effect of turbulence and the same cases were simulated with the RNG k-e turbulent model with enhanced wall treatment and thermal effects on buoyancy enabled.



a) domain mesh *b) Test assembly base surface mesh*

Figure 2 Test filter assembly computational mesh:

a) Overall view and b) filter assembly top view

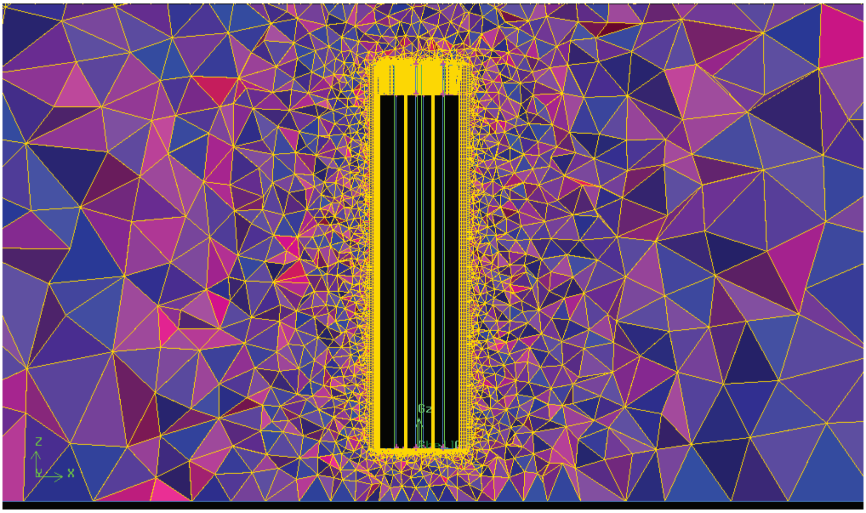


Figure 3 Computational mesh of the updated domain

Results from those simulations showed insufficient heating of the filters compared to measurements, which was later attributed to overestimation of the emissivity of the copper pipes and the simulations were repeated for a lower value of this parameter that was researched from literature [2],[3].

Calculated filter temperatures are presented in ***Figure 4***. The maximum happens to be around 276°C. Predictions of filter temperatures are compared to actual measurements in ***Figure 5*** for four laminar flow cases with copper emissivity of 0.95. It is seen that measured filter temperatures are not captured very well, and the predicted temperature gradient is not as steep as the measured one. The latter can be explained by the small convective heat exchange under laminar conditions that keeps the filter temperatures more uniform. Therefore the emissivity was updated to reflect the new findings in literature and the flow was simulated under turbulent flow regime as well. The filter temperatures for those cases are compared to measurements on ***Figure 6*** with a much better agreement.

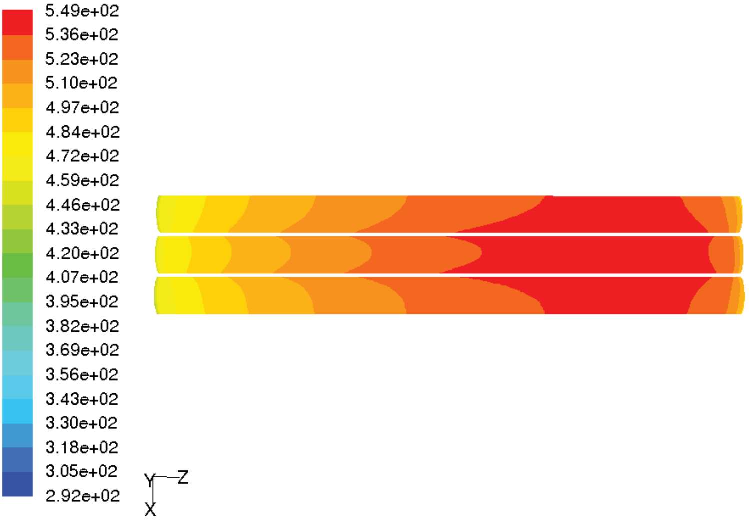


Figure 4 Filter surface temperatures

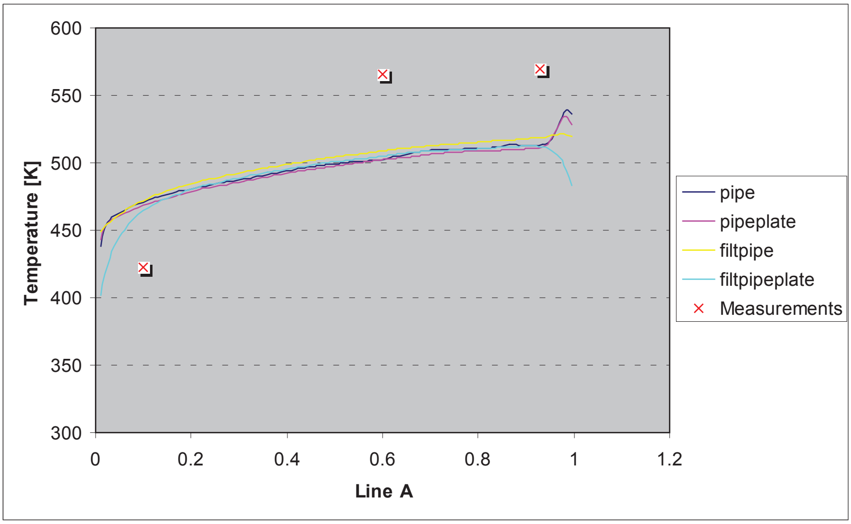


Figure 5 Filter temperatures as predicted by laminar flow simulations with copper emissivity of 0.95

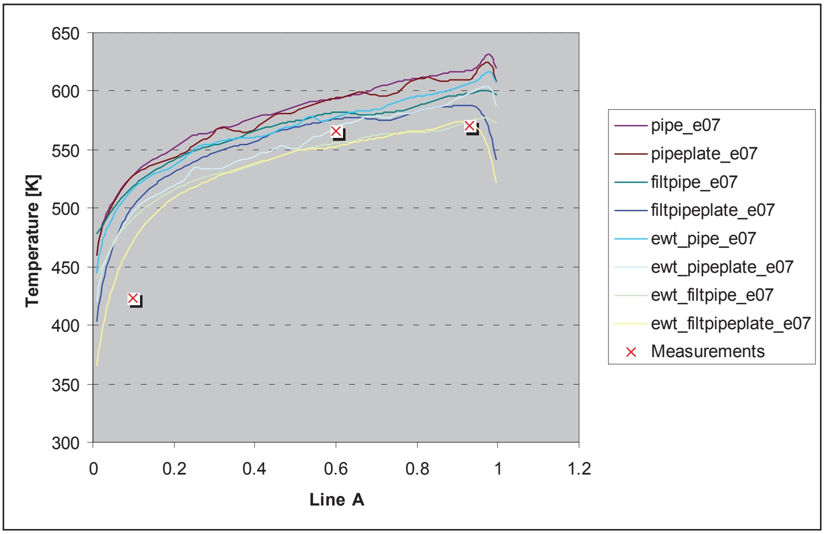


Figure 6 Filter temperatures as predicted by laminar and turbulent flow simulations with copper emissivity of 0.07

CONCLUSION

The agreement between measurements and simulations was relatively good regarding the filter temperature distribution when copper pipe emissivity was changed to reflect literature values. To model buoyancy effects the incompressible ideal gas model was used. The k-e flavours of turbulence models have tendency to overestimate the heat transfer under certain conditions. This lead to discrepancy with measured values of pipe cooling that ware however minimal when copper pipe emissivity was updated. Nevertheless, laminar flow conditions (that were also suggested by Raleigh criteria) predicted on average lower heat exchange that was in good agreement with measurements. The inclusion of a radiant heat transfer in the problem is mandatory due to the high temperature difference. The Discrete Ordinates model did perform well in this respect. The validated CFD simulations were later used to model the performance of real prototypes to be used in nuclear power plant installations.

References

[1]. Wolski A., D. Markov, G. Pichurov, E. Ivanov, P. Bakardziev, CFD thermal analysis of aerosol filters used in severe accident containment venting systems, Proc. International Conference & Workshop REMOO-2015, 23–24 September 2015, Budva, Montenegro.
[2]. http://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html
[3]. http://www.infrared-thermography.com/material.htm

За контакти:

Доц. д-р инж. Георги Пичуров, Катедра “Хидроаеродинамика и Хидравлични машини”, Технически университет – София, e-mail: george@tu-sofia.bg
Д-р Александър Волски, Уорли Парсънс, Alexander.Wolski@WorleyParsons.com

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