Verification of Heat Transfer Models in SAVANNAH Containment Thermal Hydraulic Module and Comparative Analysis with CAP and MELCOR

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1. Introduction

SAVANNAH is a module to analyze thermal-hydraulic behavior in the containment during a severe accident. It is a part of the SAFARI code, which is being developed for severe accident risk analysis. In a previous study [1], SAVANNAH predicted thermal-hydraulic behavior similar to experiments, but there were some differences compared to MELCOR results. The main reason for these differences is the heat transfer model. Therefore, this study performs a verification of the SAVANNAH heat transfer model using conceptual problems and comparing them with results from CAP and MELCOR.

2. Heat Transfer Model of CAP, MELCOR, and SAVANNAH

This section summarizes the heat transfer models for vertical plate geometries in each code.

2.1 Convection Model

All three codes use the McAdams correlation for natural convection. For forced convection, they all use the Dittus-Boelter correlation.

2.2 Condensation Model

The condensation models are different. CAP uses the Uchida model, which is based on experiments. SAVANNAH and MELCOR use the HMTA(Heat and Mass Transfer Analogy) model.

3. Problem Definition and Analysis Cases

To verify the heat transfer models, simple conceptual problems were designed. Maintaining constant wall temperature and volume TH states (pressure, temperature) throughout the analysis was ensured by assigning significantly large values to the volume and heat capacity.

3.1 Conceptual Problem of Natural Convection

Verification of the natural convection heat transfer model is performed using a nodal configuration consisting of a single thermal-hydraulic volume and a heat structure. The initial conditions are set at a pressure of 1 bar, a temperature of 323.15 K, and a relative humidity of 100%. The specific analysis conditions are summarized in Table I. To verify the heat transfer model across both laminar and turbulent regimes, the temperature difference between the wall and bulk fluid, as well as the characteristic length, are employed as the primary variables.

Table I: Test Condition for Verification of Natural Convection

Case	ΔT^* [K]	L_c [m]	Phase [-]
NC_1	1.0	1.0	Liquid
NC_2	10.0	1.0	
NC_3	1.0	10.0	
NC_4	10.0	10.0	
NC_5	1.0	1.0	Vapor
NC_6	10.0	1.0	
NC_7	1.0	10.0	
NC_8	10.0	10.0	

*temperature difference between wall and bulk

3.2 Conceptual Problem of Forced Convection

For the verification of forced convection, a nodal configuration comprising one volume, one heat structure, and two flow boundaries is utilized. The initial conditions are defined by a pressure of 1 bar, a bulk temperature of 323.15 K, and a wall temperature of 333.15 K. The detailed analysis parameters are presented in Table II.

Table II: Test Condition for Verification of Forced Convection

Case	Velocity [m/s]	D_h [m]	Phase [-]
FC_1	1.0	0.01	Liquid
FC_2	10.0	0.01	
FC_3	1.0	0.1	
FC_4	10.0	0.1	
FC_5	1.0	0.1	Vapor
FC_6	10.0	0.1	
FC_7	1.0	1.0	
FC_8	10.0	1.0	

3.3 Conceptual Problem of Condensation

The condensation heat transfer model is verified using the same nodal configuration as the natural convection case. The corresponding analysis conditions are detailed in Table III.

Table III: Test Condition for Verification of Condensation

Case	ΔT^* [K]	Humidity [%]	T_{bulk} [K]
CD_1	10.0	100	323.15
CD_2	25.0	100	
CD_3	10.0	50	
CD_4	25.0	50	
CD_5	10.0	100	373.15
CD_6	25.0	100	
CD_7	10.0	50	
CD_8	25.0	50	

*temperature difference between wall and bulk

4. Results

4.1 Verification of Natural Convection Model

Table IV presents the analysis results of the natural convection heat transfer for each code. While MELCOR and SAVANNAH predicts similar heat flux generally, CAP predicted relatively higher values. This discrepancy is attributed to the implementation of the McAdams correlation in Equation (1), where MELCOR and SAVANNAH utilize a coefficient of n = 0.1 for the turbulent regime, whereas CAP uses n = 0.13. Given that the influence of these coefficient differences is appropriately reflected in the results.

$$Nu = nRa^m \tag{1}$$

Table IV: Comparison of Heat Flux for Natural Convection Cases

Case	CAP	MELCOR	SAVANNAH
NC_1	3.1402E+02	2.4492E+02	2.4013E+02
NC_2	7.1075E+03	5.4073E+03	5.1745E+03
NC_3	3.1402E+02	2.4492E+02	2.4013E+02
NC_4	7.1075E+03	5.4073E+03	5.1745E+03
NC_5	1.3916E+00	1.4567E+00	1.4324E+00
NC_6	3.1685E+01	2.6058E+01	2.5472E+01
NC_7	1.3735E+00	1.1096E+00	1.4324E+00
NC_8	3.1685E+01	2.6058E+01	2.5472E+01

4.2 Verification of Forced Convection Model

According to the forced convection analysis results in Table V, SAVANNAH generally predicted heat flux levels consistent with the other two codes. However, significant deviations were observed in cases FC_4 and FC_8 compared to CAP, and in cases FC_5 and FC_7 compared to MELCOR. Since the forced convection heat transfer models are identical across all three codes, further investigation is required to ensure that the analysis was conducted under strictly consistent conditions.

Table V: Comparison of Heat Flux for Forced Convection Cases

Case	CAP	MELCOR	SAVANNAH
FC_1	8.8950E+04	8.8525E+04	8.7358E+04
FC_2	2.8128E+05	2.7995E+05	2.7625E+05
FC_3	2.8128E+04	2.7994E+04	2.7627E+04
FC_4	8.8950E+04	3.7553E+05	3.9922E+05
FC_5	1.2445E+02	4.6338E+01	1.1896E+02
FC_6	3.9354E+02	3.8518E+02	3.7559E+02
FC_7	3.9354E+01	2.9229E+01	3.8580E+01
FC_8	1.2445E+02	3.3044E+02	3.5046E+02

4.3 Verification of Forced Convection Model

Table VI illustrates the condensation heat flux results for the three codes. CAP and SAVANNAH demonstrated physical consistency by showing no condensation in non-condensing conditions (CD_3 and CD_7), where the wall temperature exceeded the saturation temperature. In these specific cases, the heat flux predicted by SAVANNAH is interpreted as being driven solely by convective heat transfer. In contrast, MELCOR yielded exceptionally low heat flux across all cases, suggesting that the condensation heat transfer model was not activated even under favorable condensing conditions. A follow-up analysis will be conducted to address this issue.

Table VI: Comparison of Heat Flux for Condensation Cases

Case	CAP	MELCOR	SAVANNAH
FC_1	7.2034E+02	6.8849E+00	3.4068E+02
FC_2	1.7942E+03	1.7212E+01	7.5376E+02
FC_3	0.0000E+00	2.5911E+01	2.5531E+01
FC_4	4.7333E+02	6.9500E+01	2.9657E+02
FC_5	1.5303E+04	3.4509E-01	2.2752E+03
FC_6	3.9136E+04	3.4509E-01	7.7791E+03
FC_7	0.0000E+00	2.3749E+01	2.4197E+01
FC_8	2.0880E+03	8.0168E+01	1.3419E+03

5. Conclusions

In this study, verification of natural convection, forced convection, and condensation heat transfer was performed to ensure the proper implementation of the heat transfer models in SAVANNAH, the containment analysis module of the SAFARI code.

In the natural convection analysis, SAVANNAH predicted heat flux levels similar to MELCOR; however, it predicted lower heat flux compared to CAP due to differences in the correlation coefficients. For forced convection, all three codes predicted similar heat flux levels, with the exception of a few specific cases. Finally, regarding the condensation heat transfer model verification, the three codes showed different results, and the reasons for these differences will be studied in the future.

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