

Assessment of MARS-KS Condensation and Pool Modeling Options for the i-SMR Passive Auxiliary Feedwater System Using PASCAL Test Data

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1. Introduction

The Passive Auxiliary Feedwater System (PAFS) removes the primary-side decay heat by condensing steam inside slightly inclined (3°) horizontal U-tubes submerged in an Emergency Cooling Tank (ECT), driven by two-phase natural circulation and without any AC power. The innovative Small Modular Reactor (i-SMR) adopts the same PAFS concept as the APR+, retaining the prototypical tube geometry but with fewer tubes consistent with its lower decay heat [1]. The heat-removal capability of the system is therefore governed by the in-tube condensation heat transfer coefficient (HTC), and the predictive accuracy of the system code used in licensing directly determines the reliability of the safety analysis.

In MARS-KS the default in-tube condensation package takes the maximum of the Nusselt, Shah and Chato correlations [2]. Assessments against the PASCAL separate-effect data [3] have repeatedly shown that this package under-predicts the local HTC in nearly horizontal tubes. As an alternative, MARS-KS provides Option 98, which activates the partitioned condensation model developed at Pusan National University (PNU) [4]. On the pool side, the default Chen flow-boiling correlation may be replaced by heat-transfer mode 134, which combines the Forster–Zuber pool-boiling correlation with the ESDU horizontal-bundle cross-flow correlation [2]. Finally, the ECT can be represented either by a three-dimensional MULTID component or by a one-dimensional chain of pipe nodes.

Each of these options has been examined individually, but a systematic assessment that simultaneously isolates (i) the in-tube condensation option, (ii) the pool-side boiling option and (iii) the dimensionality of the ECT, over the full PASCAL power range, has not been reported. The present work closes this gap with an eight-case matrix, evaluates the results with a tube-integrated metric, benchmarks them against the improved SPACE prediction [5], and derives a recommended modeling envelope for i-SMR PAFS analysis.

2. Analysis Method

2.1. PASCAL tests

PASCAL simulates a single tube of the 240-tube APR+ PAFS bundle at prototypical pressure, preserving the

tube inner/outer diameter (44.8/50.8 mm), the 8.4 m tube length, the 3° leg inclination and the ≈ 16 m elevation difference that drives the natural circulation [3]. Four quasi-steady tests, listed in Table I, were selected; they cover 200–750 kW, i.e. the 0.85–6.74 MPa range that brackets the i-SMR PAFS operating window. Local HTCs are available at eleven axial positions, derived from the measured top and bottom wall temperatures; their arithmetic mean is used here as the average local HTC.

Table I: Boundary conditions of the four quasi-steady PASCAL tests [3, 5]; the ECT collapsed water level is 9.30 m in all four tests

Test ID	Power (kW)	Inlet P (MPa)	Inlet flow (kg/s)
SS-200-P1	199.8	0.846	0.0937
SS-300-P1	299.8	1.342	0.1469
SS-540-P1	540.0	3.220	0.2953
SS-750-P1	750.2	6.736	0.4302

2.2. MARS-KS model and calculation matrix

MARS-KS V2.0 was used throughout. The steam generator, the steam supply line and the return water line are represented by one-dimensional components. The condensation heat exchanger tube is divided into 28 axial nodes that follow the actual inclination of each segment, including the U-bend, and the tube wall is modeled by a heat structure. The ECT is represented either by a MULTID component of $1 \times 16 \times 22$ cells or by a chain of 22 vertically stacked pipe nodes (Fig. 1). The ECT junction form losses were calibrated against the measured quasi-steady pool temperature; no in-tube quantity was tuned, so the results of Section 3 are predictions.

Eight cases (Table II) were obtained by combining two ECT dimensionalities, two in-tube condensation options and two pool-side boiling options. In the PNU model the tube perimeter is partitioned at the stratification angle γ_1 between film condensation on the steam-wetted upper part and forced-convection condensation through the falling liquid film on the lower part [4]:

$$h_{c,PNU} = [h_{film} (2\pi - \gamma_1) + h_{conv} \gamma_1] / 2\pi \quad (1)$$

with γ_1 obtained from the void fraction computed by the code. Each case was run for the four tests, giving 32

simulations; results were extracted when the ECT collapsed level reached 9.30 m, consistent with the experimental quasi-steady criterion [3].

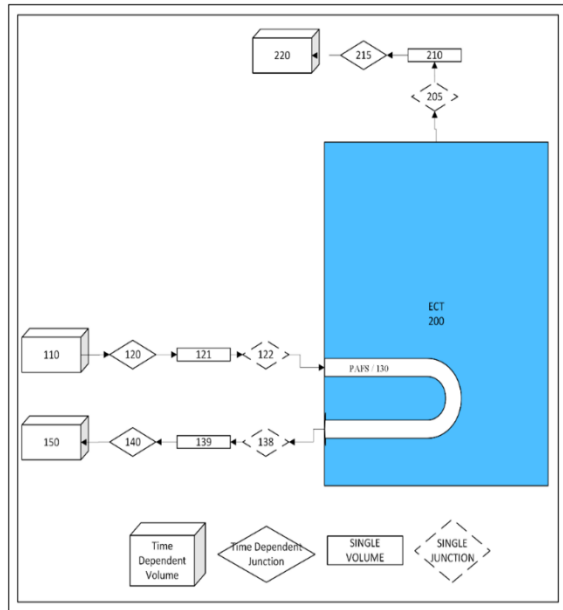


Fig. 1. MARS-KS nodalization of the PASCAL facility; the PCHX tube (PAFS130) is connected to ECT (ECT 200).

Table II: MARS-KS calculation matrix; cases A–D are the 1D counterparts of cases 0–3

Case	ECT	In-tube option	Pool-side option
0	3D	Default	Chen
1	3D	PNU (Opt. 98)	Chen
2	3D	Default	Mode 134
3	3D	PNU (Opt. 98)	Mode 134
A	1D	Default	Chen
B	1D	PNU (Opt. 98)	Chen
C	1D	Default	Mode 134
D	1D	PNU (Opt. 98)	Mode 134

Default = max (Nusselt, Shah, Chato); Chen = default flow-boiling correlation; Mode 134 = Forster–Zuber pool boiling combined with the ESDU horizontal-bundle cross-flow correlation [2].

2.3. Evaluation metric

The quantity of engineering interest is the heat removed by the whole tube rather than the coefficient at one station, so the tube-integrated average HTC is evaluated by trapezoidal integration over the measured axial range (0.55–8.21 m), applied identically to the experiment, the eight MARS-KS cases and the SPACE benchmark, so that the different axial sampling densities do not bias the comparison.

3. Results and Discussion

3.1. Tube-integrated heat transfer coefficient

The measured $\bar{h}$ is 16.8, 16.2, 17.6 and 15.4 kW m⁻² K⁻¹ [3]. Table III gives the signed deviation of the calculated $\bar{h}$ and the RMSE; Fig. 2 shows the corresponding axial distribution for SS-540-P1.

Table III: Signed deviation of the tube-integrated HTC from the PASCAL data and RMSE(%) over the four tests

Case	200 kW	300 kW	540 kW	750 kW	RMSE
0	−45.6	−28.5	−9.7	+8.5	27.6
1	−12.3	−0.3	−0.4	+12.6	8.8
2	−37.0	−14.7	+10.6	+38.4	28.2
3	−5.6	+13.6	+22.7	+48.2	27.7
A	−47.1	−32.1	−14.3	+0.4	29.4
B	−13.6	−4.8	−3.7	+1.8	7.5
C	−34.1	−14.6	+9.3	+43.7	29.1
D	−6.0	+13.0	+21.8	+49.0	27.7
SPACE [5]	−12.1	−1.3	−8.0	−12.7	9.6

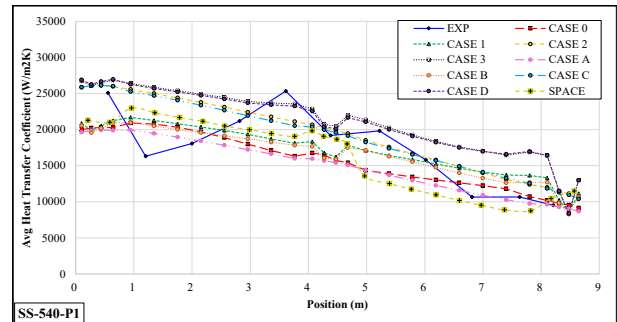


Fig. 2. Average local HTC along the PCHX tube for SS-540-P1 (3.22 MPa): experiment [3], the eight cases of Table II and the improved SPACE model [5]. The calculated profiles span the whole tube; Eq. (2) is integrated over 0.55–8.21 m only.

(i) *The in-tube condensation option dominates.* With the default package (Cases 0 and A) $\bar{h}$ is under-predicted by 46–47 % at 200 kW, and the deviation only crosses zero near 750 kW. The corresponding slope of the deviation against power is +0.083 to +0.094 % kW⁻¹, i.e. a strongly power- and pressure-dependent bias. Replacing it by the PNU model while keeping the default Chen correlation (Cases 1 and B) reduces the RMSE from about 28 % to 7.5–8.8 % and flattens the slope to +0.023~+0.037 % kW⁻¹.

(ii) *Mode 134 is detrimental in a single-tube geometry.* All four cases that activate it (2, 3, C and D) give an RMSE of at least 27.7 %. Mode 134 raises the pool-side coefficient almost uniformly along the tube, which partly compensates for the under-prediction of the default in-tube package at low power but adds to the positive bias of the PNU model at high power, reaching +48~49 % at 750 kW. In PASCAL the total resistance is dominated by

the condensation side, and a single tube offers no bundle cross-flow for ESDU to describe. Mode 134 should therefore be treated as a bundle-specific option and left inactive for single-tube validation.

(iii) *The ECT dimensionality is almost irrelevant.* The pairs (0, A), (1, B), (2, C) and (3, D) differ by less than 2 percentage points in RMSE, because the controlling thermal resistance lies inside the tube. The 1D ECT is therefore an adequate economic substitute whenever the integral heat-removal capability, rather than the pool temperature field, is the quantity of interest.

The two PNU cases (1 and B) cannot be distinguished from each other on four test points, but both are clearly separated from the remaining six. Case B is preferred because the 1D ECT is economic and its deviation-versus-power slope, $+0.023 \text{ \% kW}^{-1}$, is the flattest of the matrix. For the integral metric Case B (RMSE 7.5 %) is competitive with the improved SPACE model [5] (9.6 %), a difference that cannot be resolved with only four test points; SPACE shows smaller scatter (4.5 % versus 5.5 %) and remains the better predictor of the local HTC distribution (Fig. 2). No experimental uncertainty band is available for $\bar{h}$, so Table III should be read as indicative.

3.2. In-tube flow regime

All eight cases produce practically identical flow-regime sequences, because they share the default Mishima-Ishii horizontal-stratification criterion. The persistent transition to horizontally stratified flow is predicted at 0.6 m at 200 and 300 kW and at 4.7 m at 540 and 750 kW, against 5.0, 4.5, 2.0 and 3.5 m from the measured fluid-temperature contours [5]: the criterion is kinematic and declares stratification as soon as the vapor velocity falls below the instability threshold, before condensation has produced a resolvable liquid layer. Averaged over the four tests, the void-fraction-based criterion of the improved SPACE model [5] reduces the mean absolute displacement from 3.0 m to 2.3 m. The effect on $\bar{h}$ is moderate, but the deficiency would matter for a U-bend water-hammer analysis.

3.3. Implications for the i-SMR PAFS

Because the i-SMR PAFS keeps the prototypical tube geometry [1], the conclusions drawn for in-tube flow can be transferred directly. The long-term cooling phase is expected to proceed at an intermediate secondary pressure of roughly 3.5 MPa, held over the 72-hour grace period, so the accuracy of the code at this pressure governs the whole transient. Test SS-540-P1 (3.22 MPa) is the closest available condition, where Case B predicts $\bar{h}$ within $-3.7 \text{ \%}$ against $-14.3 \text{ \%}$ for the default package. Since the i-SMR PAFS is a bundle rather than a single tube, mode 134 should be re-activated on the pool side for the plant model, while the in-tube option validated here remains unchanged.

4. Conclusions

An eight-case MARS-KS V1.4 matrix was assessed against four quasi-steady PASCAL tests spanning 200–750 kW (0.85–6.74 MPa). The main findings are:

- The default Nusselt/Shah/Chato package underpredicts the tube-integrated HTC by up to 47 % at 200 kW, with a strongly power-dependent bias.
- Activating the PNU condensation model through Option 98 while keeping the default Chen pool-boiling correlation (Cases 1 and B) reduces the RMSE to 7.5–8.8 % and the slope to $+0.023$ – $+0.037 \text{ \% kW}^{-1}$, competitive with the improved SPACE model.
- The horizontal-bundle boiling option (mode 134) consistently worsens the agreement in the single-tube PASCAL geometry (RMSE $\geq 27.7 \text{ \%}$) and should be reserved for bundle analyses.
- The 1D and 3D ECT representations differ by less than 2 percentage points, so the simpler 1D model is sufficient for integral heat-removal predictions.
- The Mishima-Ishii criterion predicts stratification far too early at low power; a void-fraction-based criterion is recommended as a future code improvement.

For the i-SMR PAFS, Case B is recommended as the baseline for the in-tube response over the full pressure window, with mode 134 activated on the pool side for the actual bundle geometry.

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