Qualification of the system code AC$^2$ (submodule ATHLET) for the safety assessment of passive residual heat removal systems

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Outline

- AC² and ATHLET description
- Passive Residual Heat Removal Systems: The KERENA Emergency Condenser
- NOKO facility description
- ATHLET simulations of the NOKO facility: Recent and current activities
- Conclusion & Outlook
Thermal-hydraulic link in the GRS nuclear simulation chain → presentation „The Nuclear Simulation Chain of GRS“

Covers operational states, incidents, accidents, severe accidents

Comprises the GRS modules:

- **ATHLET** → primary and secondary system; no core degradation
- **ATHLET-CD** → extension for core degradation
- **COCOSYS** → containment phenomena
- **ATLAS** → post-processing tool for all modules
ATHLET

- Analysis of the Thermal-hydraulics of LEaks and Transients
- System code for comprehensive and realistic analyses of the thermal-hydraulic behavior of the coolant system of a nuclear power plant
- Substantial validation basis (LOCAs, transients, …)
- Original 1D code (2D/3D conservation equations available & under development)
- Finite volume approach on staggered grid
- Coupling with CFD and neutronics codes possible
- Focus is on the simulation of physical phenomena, not of special components (black boxes)
Passive Residual Heat Removal (PRHR) Systems

- Passive systems (cf. IAEA-TECDOC-1624):
  - Can contribute to simplification and potentially improve economics
  - Increase the reliability of the performance of essential safety functions

- PRHR: Removal of residual heat even in the case plant power is lost

- Examples:
  - AP600/1000: PRHR-HX
  - VVER-1200 (AES-2006): Steam Generator PHRS
  - KERENA: Emergency Condenser (EC)

- Challenge for ATHLET:
  - Operation usually starts on its own (i.e. no activation signal)
  - Driving forces of operation may vary during the course of a transient dependent on the boundary conditions
  - Conditions may be beyond the range of validity of implemented correlations
The KERENA Emergency Condenser (EC)

- **SWR600/1000 (Siemens AG):**
  - 4 ECs
  - Maximum heat removal capacity: 63 MW per EC

- **KERENA (AREVA) as successor of SWR600/1000:**
  - EC principle is the same, details differ (e.g. 61 condenser tubes instead of 104)

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Graphic taken from Krepper /KRE 07/
The KERENA Emergency Condenser (EC)

- Characteristics & phenomena:
  - Slightly inclined horizontal pipes
  - Condensation inside the tubes (depending on local flow pattern)
  - Convective boiling outside
  - Free convection in water pool

- Test facilities simulated with ATHLET:
  - NOKO (FZ Jülich; single component experiments)
  - TOPFLOW (HZDR; single component experiments)
  - INKA (AREVA; integral tests)

Graphic taken from Schaffrath /SAN 16/
The NOKO test facility

- Thermo hydraulic test rig, scale 1:13 resp. 1:26 (original size condenser tubes; scaled by the number of tubes used)
- Max. power of electrical heater: 4 MW
- Experiments carried out under quasistationary conditions

Nodalization scheme in ATHLET (condenser vessel only sketched)
ATHLET 3.0 simulations of the NOKO facility

![Graph showing EC power vs. (T_{Sat,prim} - T_{Sat,sec}) in K](image)

- EC power [MW]
- (T_{Sat,prim} - T_{Sat,sec}) [K]

Experiment
Code modifications ATHLET 3.0 → ATHLET 3.1

- Secondary side (subcooled/saturated nucleate boiling):
  - Convective boiling
  - Pool boiling
  - Forced convection
ATHLET 3.1 simulations of the NOKO facility

![Graph showing the comparison between experimental data and ATHLET 3.0 simulations for EC power (MW) versus \((T_{\text{Sat,prim}} - T_{\text{Sat,sec}}) [K]\).]
Current work: Joint project PANAS

- General information:
  - Funded by BMBF
  - Consortium partners: TUD-WKET, THD, AREVA GmbH, HZDR
  - GRS is a subcontractor of TUD-WKET
  - Project period: 07/2015 – 12/2018

- Project objectives:
  - Investigation of passive decay heat removal systems
  - Experimental analyses
  - Modeling and validation for system codes and CFD codes

- GRS subtask:
  - Validation and – if necessary – improvement of condensation and evaporation heat transfer models for ATHLET
PANAS: Data used for validation

- Data used for validation from COSMEA experiments performed at HZDR

- Single effect test stand
- Focus on flow patterns and condensation processes
- Secondary side cooled by convection
- Instrumentation: i.a. thermocouples and X-ray tomography system

Graphic taken from Szijártó /SZI 15/
PANAS: ATHLET modifications made so far

- Implementation of condensation heat transfer model of Thome et al.

**Flow pattern map**

*Example (R-12 at 40°C) acc. to El Hajal et al. /HAJ 03/*

**Heat transfer**

- rather mechanistic modelling
- \( htc_{ges} = f (htc_{conv}, htc_{cond}, \theta_{strat}) \)
PANAS: ATHLET modifications made so far

- Implementation of condensation heat transfer model KONWAR /SCH 96/

**Flow pattern map**

**Heat transfer**

- Combination of (semi-)empirical models for different flow regimes

\[
\frac{j_B^*}{\bar{m}} = \frac{\dot{x} \cdot \bar{m}}{A [g \cdot d \cdot \rho_v (\rho_l - \rho_v)]^{0.5}}
\]

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ATHLET 3.1 + THOME simulations of the NOKO facility

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ATHLET 3.1 + KONWAR simulations of the NOKO facility

EC power [MW] vs. \((T_{\text{Sat,prim}} - T_{\text{Sat,sec}}) [K]\)

- Experiment
- ATHLET 3.0
- ATHLET 3.1
- THOME
- KONWAR

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Conclusions & Outlook

- Conclusion
  - ATHLET 3.0 → 3.1: significant improvement of heat transfer
  - Implementation of Thome et al. and KONWAR: smaller improvements

- Next steps
  - Validation of implemented models by simulation of COSMEA experiments
  - If it proves necessary: modification of heat transfer correlations at tube bundle shell side

- Moreover: Joint project EASY (03/2015 – 02/2018; focused on integral tests at INKA)
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