Analysis of the corrosion test process for heat exchangers in corrosion test chambers by CFD simulation

STAR Global Conference, Wien, March 17-19, 2014

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As a leading global development partner for the automotive and engine industry, MAHLE is working on innovative products for new generations of vehicles and mobility concepts.

As of October 2013, the Behr Group - one of the leading OEMs worldwide in vehicle air conditioning and engine cooling - is integrated into the MAHLE Group as the Thermal Management business unit.
Introduction

Motivation

- Failure by corrosion is a relevant issue of aluminum heat exchangers
- Standardized corrosion tests are performed inside corrosion test chamber
- Better understanding of physical (transport) processes within corrosion test chamber (as a basis for sophisticated corrosion simulations)
- Improvement of the corrosion test process

Objectives of the analysis:

- Reliable simulation of the salt spray transport within test chamber
- Analysis of deposition of salt water (salt spray) on specimens
- Sensitivity study of influences of different boundary conditions and test layouts

- CFD-Simulation using STAR-CCM+
Introduction

ASTM 85-11: Standard practice for modified salt spray testing

- Test for accelerated simulation of corrosive behavior of specimens under defined conditions
- Injection of salt spray solution by a twin fluid nozzle
- Control of testing procedure by two collecting funnels inside the test chamber
  - Accumulated amount of salt spray within funnel: 1 - 2 ml per (spraying) hour
  - Collecting area A = 80 cm²
- Several corrosion tests exist with different conditions: AASS test, CASS test, SWAAT, SO2 salt spray test, Dilute electrolyte cyclic fog dry test
  - SWAAT (Sea Water Acetic Acid Test)
    - 30 minutes spraying period
    - 90 minutes recovery period @100% relative humidity
    - Salt spray solution: 4.2% of salt, 1% of acetic acid
    - Temperature within test chamber T = 49°C (MAHLE Behr standard)
Simulation modeling

Simulation model of the test

- Test chamber geometry
- Steady
- Turbulent – RANS - k-ε realizable
- 1.5E6 polyhedral cells
- Simulation with STAR-CCM+

- Steady single phase simulation of air flow in test chamber
- Subsequent disperse phase simulation of distribution (tracks) of spray of salt water
Definition of boundary conditions

Characteristic of twin fluid spray nozzle

- Fluids: air and salt spray solution
- Full cone nozzle
- Experimental analysis of twin fluid spray nozzle:
  - Parameters of interest are:
    - Particle size distribution
    - Cone angle $\alpha$
    - Air flow rate $\dot{V}_{\text{air}}$
  - Variable parameters of spray nozzle are:
    - Geometric position $x$ of head of nozzle
    - Relative primary pressure of air $p_{\text{rel, nozzle}}$
    - Flow rate of salt spray solution $\dot{V}_{\text{salt}}$
Definition of boundary conditions

Characteristic of twin fluid spray nozzle

- Results of experimental analysis of characteristic of spray nozzle
- Particle size distribution and air flow rate
  - depending strongly on position of head of spray nozzle

- Spraying angle depending on position $x$

$D_{v50}$ vs. position $x$ (mm)

- $x = 8$ mm
- $x = 9$ mm
Definition of boundary conditions

Detailed simulation of twin fluid nozzle

- Analysis of air flow at the outlet of the twin fluid nozzle
  - Inlet boundary conditions of simulation of the test chamber

- Out flow of air (and salt spray) not occupying the complete geometric exit area and cone angle of the nozzle
- Inlet velocity of air flow: \( v \sim \frac{1}{d^2} \)
- Geometric diameter \( d = 6 \text{ mm} \)
- Flow diameter \( d = 3.7 \text{ mm} \)

- More accurate definition of inlet boundary conditions for simulation of test chamber possible
Simulation modeling

Setup of two phase simulation

- **Lagrangian Multiphase Model**
- **Spherical droplets (= particle)**
  - Constant density
  - Droplet size distribution is taken from experimental measurements (100 „parcel streams“)
  - Initial velocity of droplets $\nu = 0$ m/s
    (droplets are taken by air flow)
- **One-Way-Coupling** (no reverse influence of droplets to air; no particle-particle interaction)
- **Drag force of droplets**
- **Gravitational force of droplets**
- **Bai-Gosman wall interaction model**
- **Vaporization of droplets** can be neglected due to saturated atmosphere inside corrosion test chamber
Simulation of the test chamber

Bai-Gosman Wall Interaction Model

- Modeling interaction of droplets with walls

![Diagram showing different interaction modes of droplets with walls: ADHERE, REBOUND, SPREAD, BREAK-UP AND REBOUND, BREAK-UP AND SPREAD, SPLASH.]

\[ We_{l} = \frac{\rho_{p} \cdot v_{r,n}^{2} \cdot D_{p}}{\sigma} \]

- \( T_{12} = \) Boiling temperature of droplets
- \( T_{23} = \) Leidenfrost temperature of droplets
Simulation of the test chamber

Bai-Gosman Regimes

- Occurrence of four different regimes of Bai-Gosman model
  - Usage of Bai-Gosman wall interaction model is necessary
- Significant fraction of droplets is rebounded by the ceiling and hits the specimen. Not according to test standard specification!

Operating point:
- $x_{\text{prel, nozzle}} = 8 \text{ mm}$
- $\rho_{\text{rel, nozzle}} = 1 \text{ bar}$
- $V_{\text{salt}} = 1 \text{ l} / \text{h}$
Simulation of the test chamber

Comparison of experimental and numerical results

- Comparison of deposited amount of salt water in collecting funnels

- Good agreement of experimental and numerical results
Simulation of the test chamber

Variation of the boundary conditions for simulation

- Influence of position and orientation of spray injector on deposited salt water

- Very good agreement of zones plausible results of simulation for deposited salt water due to variation of injector position ($\leq 2$ cm) and angle ($\leq 10^\circ$)
Salt water droplets are injected towards the ceiling of the test chamber

- Bigger droplets (>90 μm) sink to the floor due to gravitational force
- Smaller droplets follow the gas flow and are distributed across the test chamber

**Operating point:**

\[ x = 8 \text{ mm} \]
\[ p_{\text{rel, nozzle}} = 1 \text{ bar} \]
\[ V_{\text{salt}} = 1 \text{ l/h} \]
Simulation of the test chamber

Analysis of distribution of salt water spray

- Inhomogeneous distribution of salt water spray inside the test chamber
- Improvement of distribution of salt water spray by modifying the positioning of the specimens or by modifying the test process and the test conditions could be studied

Operating point:
- $x = 8 \text{ mm}$
- $p_{\text{rel, nozzle}} = 1 \text{ bar}$
- $V_{\text{salt}} = 1 \text{ l/h}$
Simulation of the test chamber

Deposit of salt spray water

- Three zones of accumulation of salt water spray could be identified
- Less deposition of salt water spray at outer columns of specimens

Balance of deposited amounts

<table>
<thead>
<tr>
<th>Sprayed amount</th>
<th>1000 ml/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>222 ml/h</td>
</tr>
<tr>
<td>Floor</td>
<td>470 ml/h</td>
</tr>
<tr>
<td>Side walls</td>
<td>112 ml/h</td>
</tr>
<tr>
<td>Air outlet</td>
<td>108 ml/h</td>
</tr>
<tr>
<td>Other parts</td>
<td>5 ml/h</td>
</tr>
<tr>
<td>Specimens</td>
<td>83 ml/h</td>
</tr>
</tbody>
</table>

Operating point:
- \( x = 8 \text{ mm} \)
- \( p_{\text{rel, nozzle}} = 1 \text{ bar} \)
- \( V_{\text{salt}} = 1 \text{ l/h} \)
Injector inclined to the left by $10^\circ$

- Deposited salt water on specimens: 88 ml/h

**Operating point:**
- $x = 8 \text{ mm}$
- $p_{rel, nozzles} = 1 \text{ bar}$
- $V_{salt} = 1 \text{ l/h}$
Simulation of the test chamber

Variation of position and angle of injector

- Injector dislocated backwards by 2 cm (from center of chamber)

- Strongly directed flow of droplets to the front side of the chamber induced by the reflection from the cover

- Significant number of droplets encounter the specimens directly

- Massively increased amount of deposited salt water at the front side of the chamber

Operating point:
- $x = 8 \text{ mm}$
- $p_{\text{rel, nozzle}} = 1 \text{ bar}$
- $V_{\text{salt}} = 1 \text{ l/h}$
Injector inclined backwards by 10°

Operating point:
\[ x = 8 \text{ mm} \]
\[ p_{\text{rel, nozzle}} = 1 \text{ bar} \]
\[ V_{\text{salt}} = 1 \text{ l/h} \]

- Strongly directed flow of droplets to the front side of the chamber induced by the reflection from the cover
- Significant number of droplets encounter the specimens directly
- Massively increased amount of deposited salt water at the front side of the chamber
Comparison of different positions of nozzle head

- Distribution of salt spray for position of nozzle head of x = 7 mm
  - Generally bigger droplet sizes
  - Lower inlet velocity of air flow

- Deposited amount of salt water on specimens: x = 7 mm: 36 ml/h
  x = 8 mm: 83 ml/h

Operating point:
- x = 7 / 8 mm
- $p_{rel, nozzle} = 1$ bar
- $V_{salt} = 1$ l/h
CFD simulation of corrosion test process

Summary and Outlook

- **Summary**
  - Determination of reliable boundary conditions for simulation of the test chamber by experimental and numerical study of the spray nozzle
  - First analysis of the corrosion test process and sensitivity study of the influencing parameters have shown a strong influence of the positioning of the injector on the salt water spray deposition
  - Simulation of test chamber enables further sensitivity studies of different influencing parameters on corrosion test

- **Outlook**
  - Further analysis and improvement of existing corrosion test process
  - Detailed simulation of corrosion process
  - Complete simulation of virtual corrosion test process in the future?