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The Addition of Noncondensable Gases into RELAP5-3D for Analysis of High-Temperature Gas-Cooled Reactors

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2003 RELAP5 International User’s Seminar
West Yellowstone, Montana

August 27 - 29, 2003
Introduction

• RELAP5-3D/ATHENA is being developed for analysis of high-temperature gas-cooled reactors
• The graphite in the core can oxidize due to air ingress following a loss-of-coolant accident
• The oxidation results in the formation of carbon dioxide and carbon monoxide
• A graphite oxidation model was previously added to the code using internal laboratory funding
• Oxygen, carbon dioxide, and carbon monoxide noncondensable gases were added to the code to support the analysis of graphite oxidation in gas-cooled reactors
Introduction (continued)

- The temperature range of interest is from 395 to 2073 K
- The inclusion of an additional gas species requires a gas constant and correlations for specific internal energy, thermal conductivity, and viscosity, and diffusion parameters
- The implementation of the new gas species was funded by DOE’s Korean International Nuclear Energy Research Initiative
The original noncondensable model:

- Assumes that each noncondensable species is an ideal gas with the specific internal energy a function of temperature alone
  - Linear for $T < 250$ K
  - Quadratic for $T > 250$ K

- This implies that the specific heat, $C_v$, is
  - Constant for $T < 250$ K
  - Linear for $T > 250$ K

- Internal energy correlations for the existing noncondensable gases (helium, hydrogen, nitrogen, etc) were fit from 250 to 700 K, much lower than the range of interest for gas-cooled reactors
The original form of the equation was not adequate at high temperatures

- $C_v$ is not linear at temperatures above 700 K for the new noncondensable gases
- The original form of the equation was replaced by a more general, fourth-order polynomial
  - $C_v$ is a cubic function of temperature for $T > 250$ K
- Coefficients were determined by least squares fits to data presented in Avalone (1987) and Rivken (1988)
- The higher order form was applied to all the code’s noncondensable gases, but the higher order coefficients were set to zero for the original gases so that results were not altered
The new model represents the internal energy well over the required temperature range.
The new model represents $C_v$ well over the required temperature range.

- Oxygen

- Avallone (1987)
- Rivken (1988)
- Lemmon et al. (2002)
- Kayes and Crawford (1980)
- Reynolds (1979)

$C_v$ ($\text{kJ/kg-K}$) vs. Temperature (K)
Similar results were obtained for CO$_2$ and CO

![Graph showing $C_v$ (kJ/kg-K) vs. Temperature (K) with various data points and a fit line.](Image)

- CO$_2$

  - Avallone (1987)
  - Rivken (1988)
  - Lemmon et al. (2002)
  - Kayes and Crawford (1980)
  - Reynolds (1979)

  Fit
Transport properties were also implemented for the new species

- The same functional form was used as for the existing species
  - Coefficients were determined by least squares fits to the data presented by Lemmon et al. (2002)
The new fits represent the thermal conductivity data reasonably well.

- Lemmon et al. (2002)
- Daubert et al. (2000)
- Kayes and Crawford (1980)
- MATPRO

thermconductivity (W/m-K)

Temperature (K)
The new fits represent the thermal conductivity data reasonably well.

- Lemmon et al. (2002)
- Daubert et al. (2000)
- Kayes and Crawford (1980)
- MATPRO

**Fit**

- $\text{CO}_2$
The new fits represent the viscosity data reasonably well.

![Graph showing viscosity data and fits for different studies.](image-url)
Diffusion parameters were also implemented for the new species

- The presence of a noncondensable gas can significantly affect the heat transfer coefficient during condensation
- Binary diffusion coefficients were calculated using the same method as for the existing noncondensable gases
  - The coefficients apply to diffusion of a steam/noncondensable mixture to the surface of a water film
Conclusions

• The code’s original (quadratic) noncondensable gas model was not adequate for the new gas species at high temperatures

• A fourth order polynomial represented the internal energy well between 250 and 3000 K
  – Maximum deviations were 2.2% for internal energy and 7% for $C_v$
  – Maximum deviations occurred at the temperature extremes
Conclusions (continued)

• The transport properties were in reasonable agreement
  – Maximum deviations were less than 4% for O₂ and CO and less than 12% for CO₂

• The correlations for the original noncondensable gases could be improved using the new fourth order polynomial