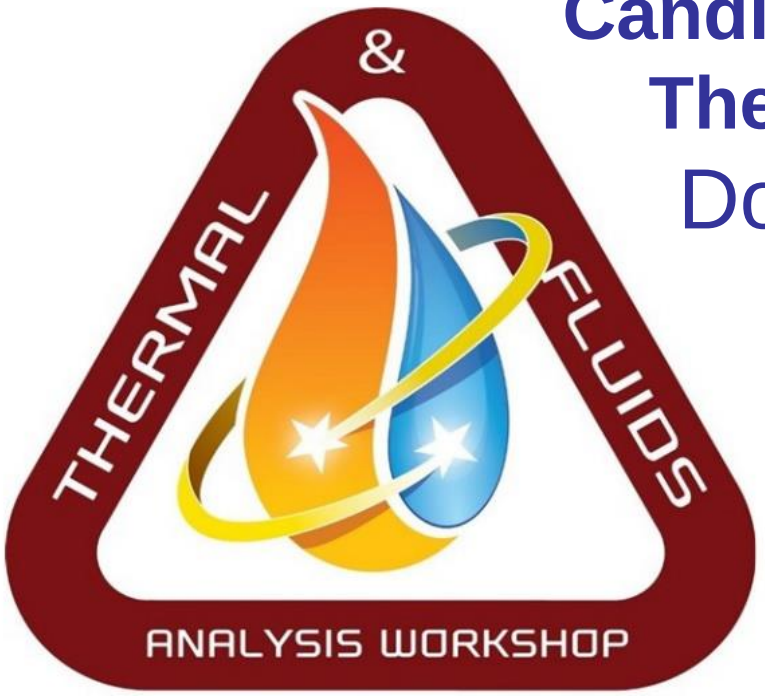

Candidate Benchmark Cases for Thermal and Fluid Software

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What is a Benchmark Case?

- Benchmark
  - A standard against which things are compared or assessed

- Benchmark case
  - A description of a system to be modeled
    - Simple
    - Easy to model
    - Quick to solve
    - Accepted solution

The Case for Benchmark Cases

- Thermal and fluid software used for passive and active thermal designs lacks a standardized set of benchmark cases
  - NPARC has an established set for computation fluid dynamics
  - NAFEMS has an established set for finite elements
    - Primary focus is structural solutions, but some thermal cases have been established; most of the thermal cases are included in this paper.
- Uses for benchmark cases
  - Verify – compare with a closed-form solution (Roache)
  - Validate – compare with an experiment or other established solution (Roache)
  - Compare software products
  - Evaluate software capabilities
  - Train new employees
  - Verify installation

Benchmark Case Descriptions

- Reference
- Case features
  - Dimensions
    - Solution (0D, 1D, 2D, 3D)
      - What is the solution dimension?
    - Geometry (0D, 1D, 2D, 3D)
      - What model objects can be used?
  - Physics
    - What is being solved?
  - Boundary conditions
    - What is being applied?
  - Time dependence
    - Steady state, transient, or both?
  - Comparison
    - Is there a closed-form solution?
- What? No problem statement?
  - The answer for comparison can be determined by the governing body or the user

Sketch if available

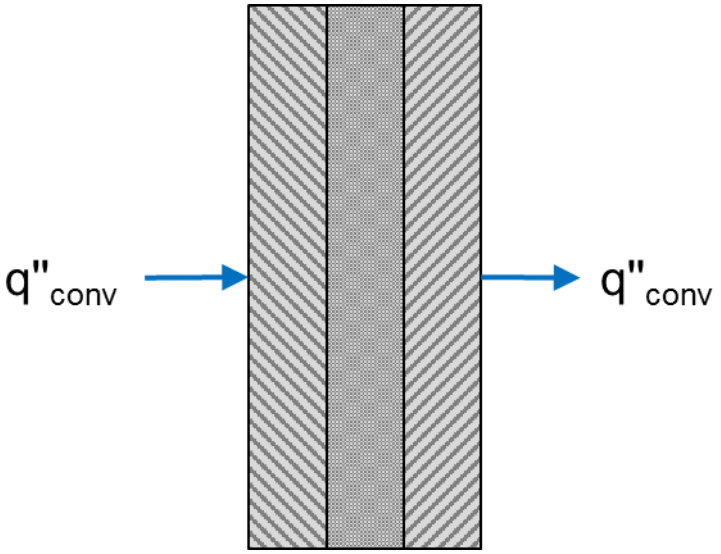
HEAT TRANSFER CASES

HT001 – Conduction with Radiation

- Davies, Fenner, & Lewis, 1993, pp. 101-106
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
- Boundary conditions
  - Temperature
  - Radiation
- Time dependence
  - Steady state
- Comparison
  - Closed-form solution

HT002 – Composite Wall

- Bejan, 1993, pp. 37-38
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
  - Composite materials
- Boundary conditions
  - Convection
- Time dependence
  - Steady state
- Comparison
  - Closed-form solution

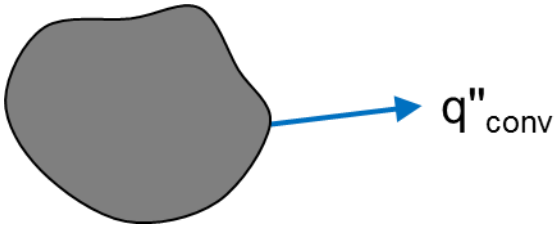


HT003 – Contact Joint

- Holman, 1986, p. 58
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
  - Thermal contact
- Boundary conditions
  - Temperature
- Time dependence
  - Steady state
- Comparison
  - Closed-form solution

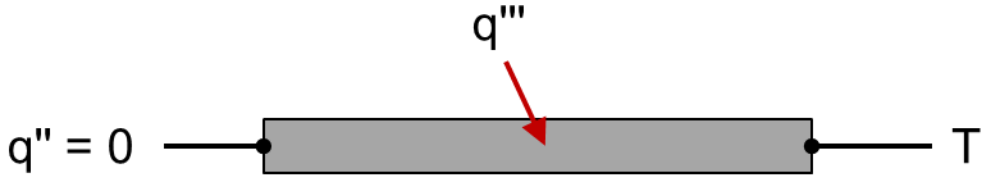
HT004 – Lumped Capacitance

- Holman, 1986, pp. 135-136
- Dimensions
  - 0D (zero D) solution
  - 0D, 2D, or 3D geometry
- Physics
  - Lumped capacitance
- Boundary conditions
  - Convection
- Time dependence
  - Transient
- Comparison
  - Closed-form solution



HT005 – Conduction with Internal Heat Generation

- Casey & Simpson, 1986, p. 2.3
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
  - Heat generation
- Boundary conditions
  - Temperature
- Time dependence
  - Transient
- Comparison
  - Closed-form solution

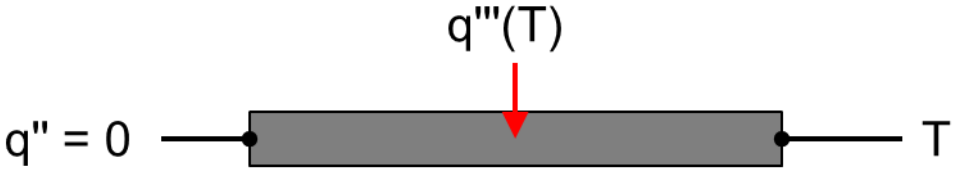


HT006 – Oscillating Temperature BC

- Davies, Fenner, & Lewis, 1993, p. 107
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
- Boundary conditions
  - Temperature
  - Transient
- Time dependence
  - Transient
- Comparison
  - Closed-form solution

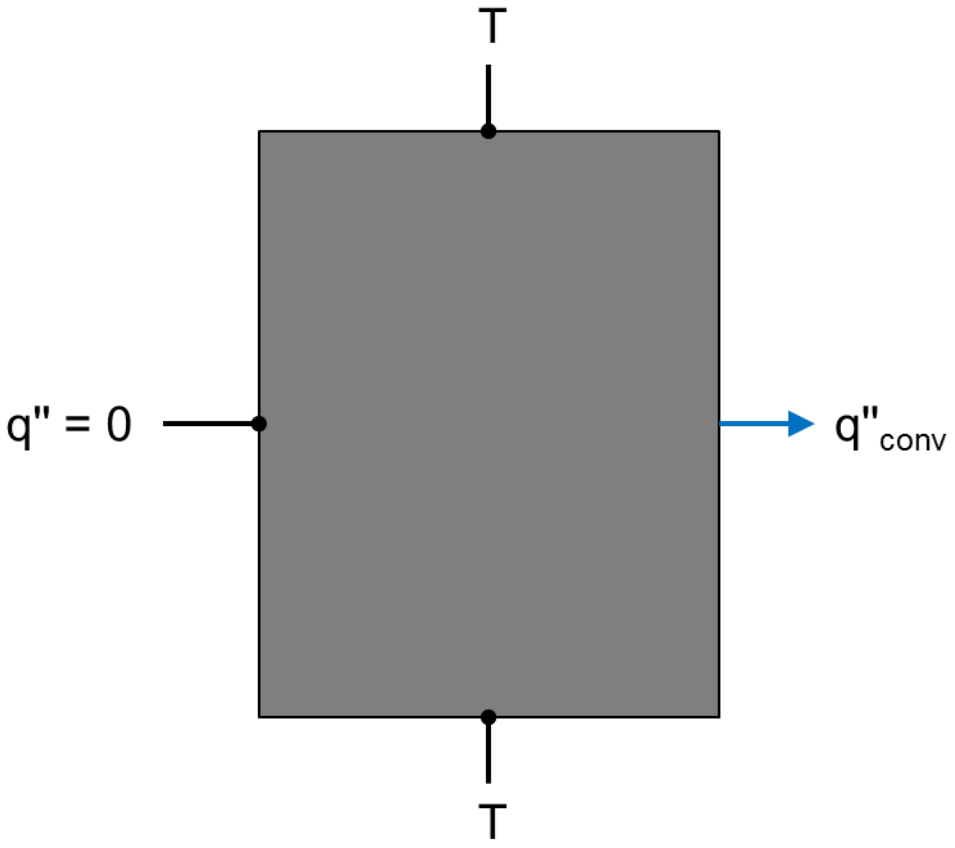
HT007 – Temperature-Dependent Heat Generation

- Casey & Simpson, 1986, p. 2.5
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
  - Heat generation
  - Variable properties
- Boundary conditions
  - Temperature
- Time dependence
  - Transient



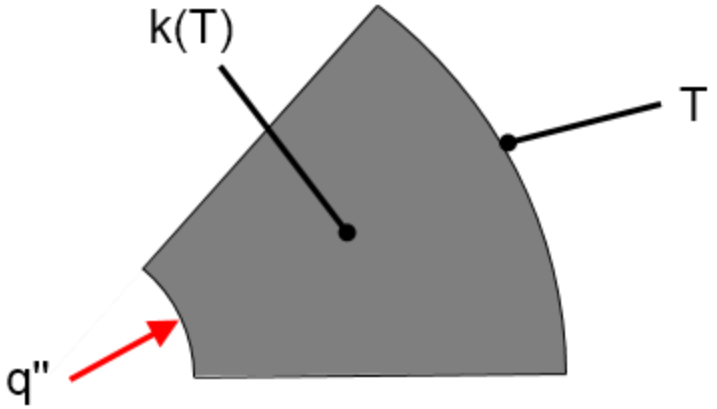
HT008 – 2D Conduction with Convection

- Casey & Simpson, 1986, p. 2.8
- Dimensions
  - 2D solution
  - 2D or 3D geometry
- Physics
  - Conduction
- Boundary conditions
  - Convection
  - Temperature
- Time dependence
  - Steady state



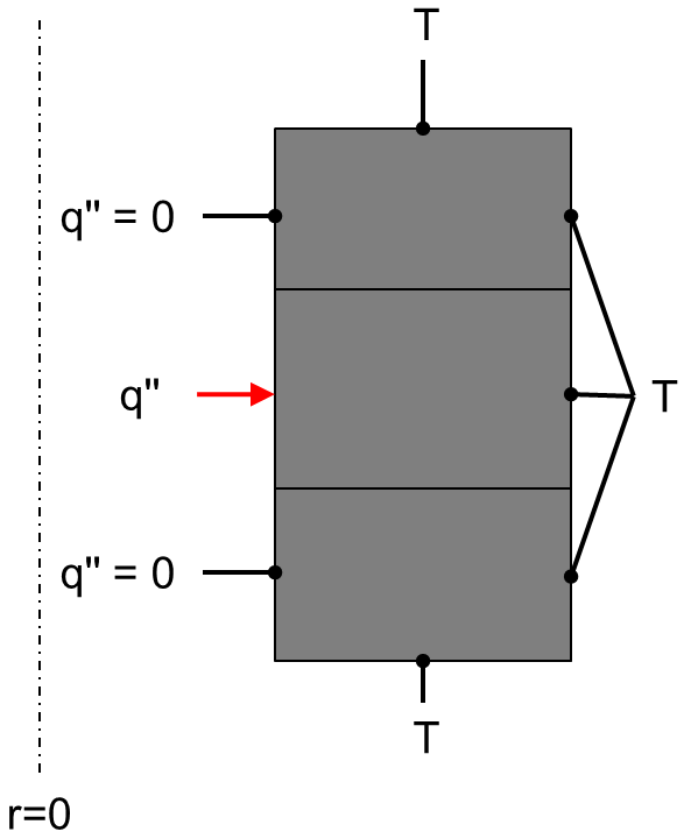
HT009 – Temperature-Dependent Conductivity

- Casey & Simpson, 1986, p. 2.9
- Dimensions
  - 1D solution
  - 1D, 2D, or 3D geometry
- Physics
  - Conduction
  - Variable properties
- Boundary conditions
  - Heat flux
  - Temperature
- Time dependence
  - Steady state



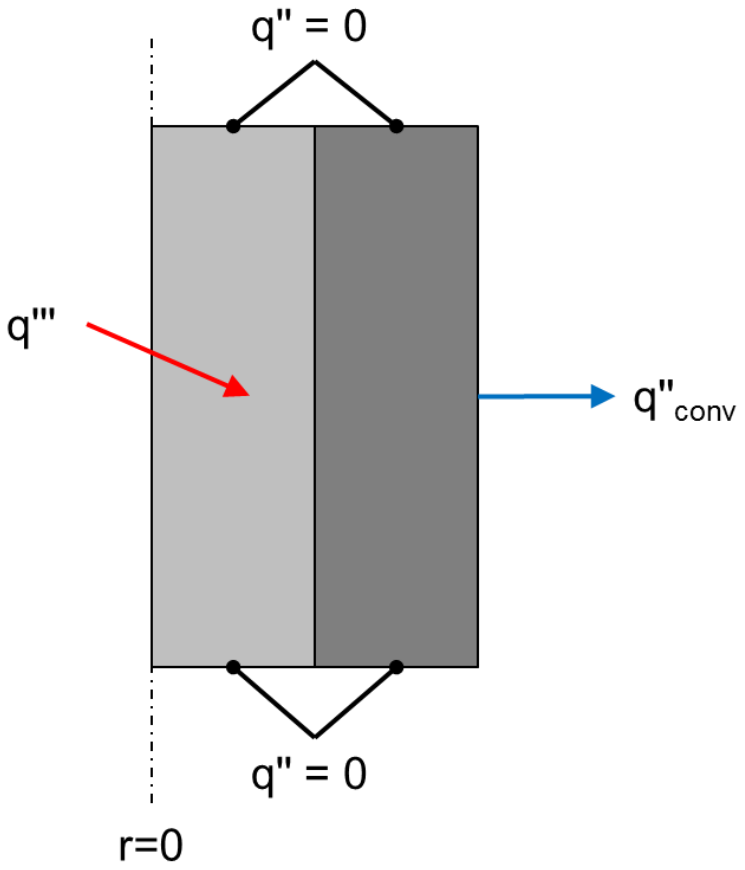
HT010 – Discontinuous Flux

- Casey & Simpson, 1986, p. 2.11
- Dimensions
  - 2D solution
  - 2D or 3D geometry
- Physics
  - Conduction
- Boundary conditions
  - Heat flux
  - Temperature
- Time dependence
  - Steady state



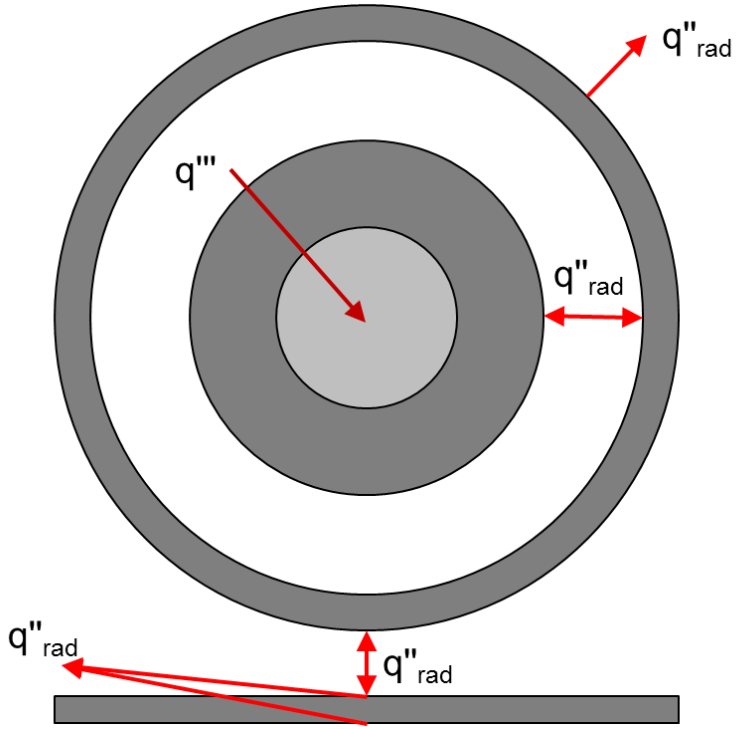
HT011 – Composite with Heat Generation

- Glass, et al., 1988, pp. 4-7
- Dimensions
  - 2D solution
  - 2D or 3D geometry
- Physics
  - Conduction
  - Heat generation
  - Composite materials
- Boundary conditions
  - Convection
- Time dependence
  - Steady state
  - Transient



HT012 – Conduction and Radiation with Heat Generation

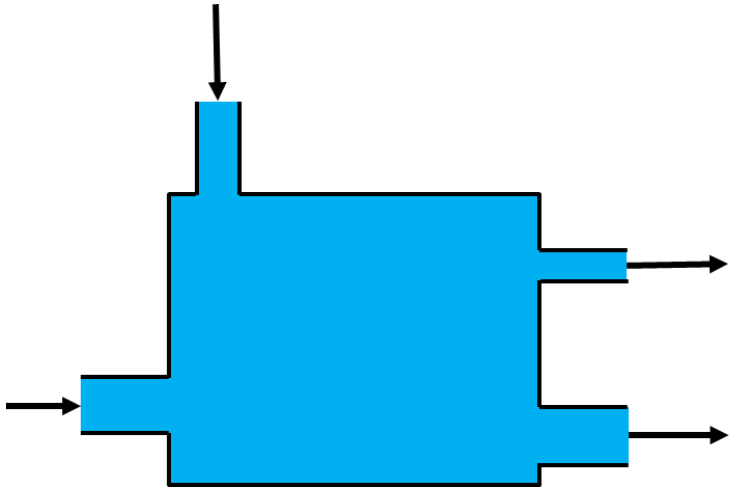
- Glass, et al., 1988, pp. 8-10
- Dimensions
  - 2D solution
  - 2D or 3D geometry
- Physics
  - Conduction
  - Composite materials
  - Heat generation
  - Radiation
- Boundary conditions
  - Radiation
  - Symmetry
- Time dependence
  - Steady state
  - Transient



FLUID FLOW CASES

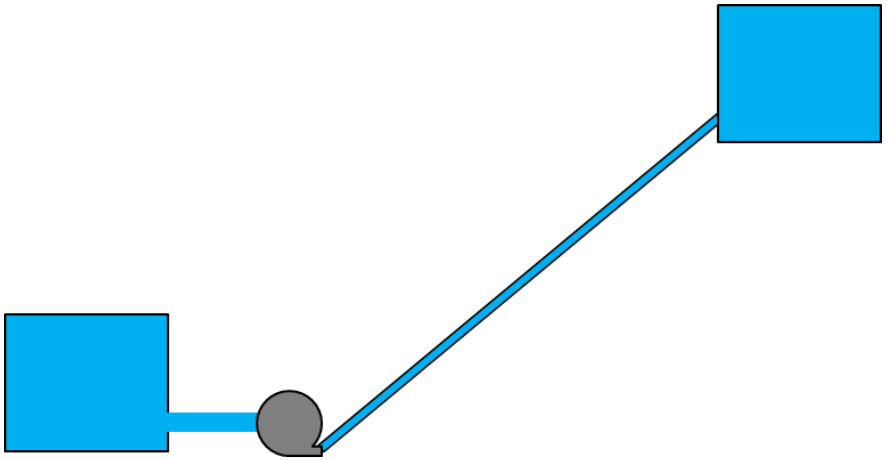
FF001 – Multi-Inlet, Multi-Outlet Steady Flow

- Crowe, Elger, & Roberson, 2001, pp. 122-123
- Dimensions
  - 0D (zero D) solution
  - 0D or 3D geometry
- Physics
  - Lumped capacitance
  - Fluid flow
- Boundary conditions
  - Mass flow rate
- Time dependence
  - Steady state
- Comparison
  - Closed-form solution
- Variations
  - Transient solution
  - Adiabatic and compressible
  - Real gas



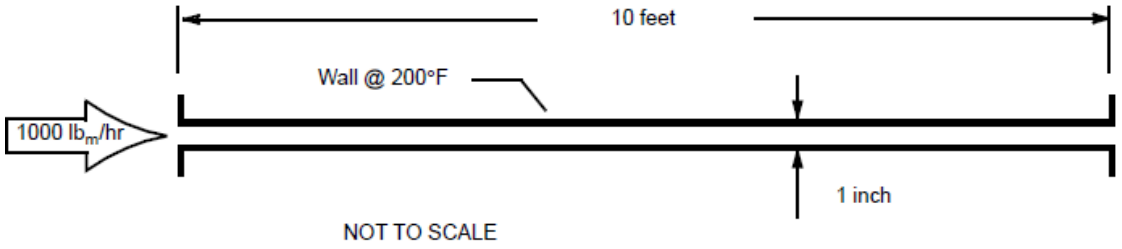
FF002 – Pump and Pipe System

- Gerhart & Gross, 1985, pp. 476-480
- Dimensions
  - 1D solution
  - 1D geometry
- Physics
  - Fluid flow
- Boundary conditions
  - Hydrostatic pressure
  - Pipe system with losses
  - Single-curve pump
- Time dependence
  - Steady state
- Comparison
  - Closed-form solution



FF003 – Internal Fluid Flow with Convection

- Dimensions
  - 1D solution
  - 1D geometry
- Physics
  - Fluid flow
  - Convection
- Boundary conditions
  - Temperature
  - Mass flow rate
- Time dependence
  - Transient
- Comparison
  - Closed-form solution



FF004 – Boiling

- Physics
  - Convection
  - Phase change

- Specific case not identified, yet.

FF005 – Water Hammer

- Wylie & Streeter, 1982
- Dimensions
  - 1D solution
  - 1D geometry
- Physics
  - Pressure wave
  - Compressible liquids
- Time dependence
  - Transient
- Comparison
  - Method of Characteristics

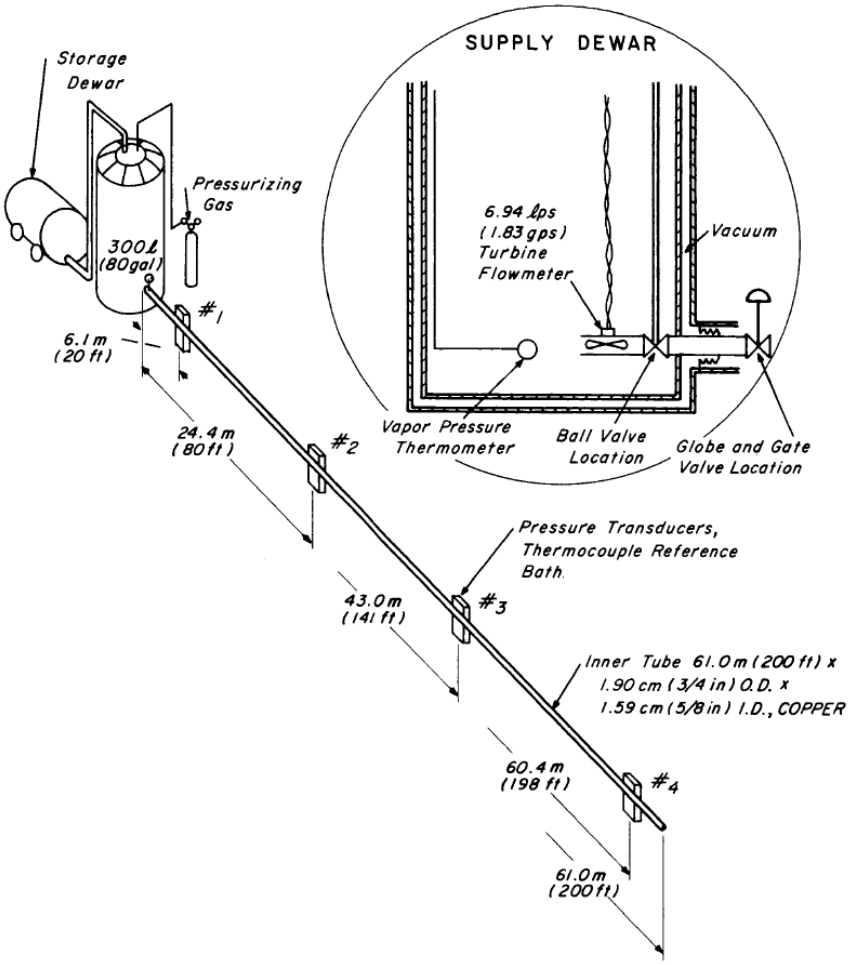
FF006 – Water Hammer (line priming)

- Dimensions
  - 1D solution
  - 1D geometry
- Physics
  - Pressure wave
  - Compressible liquids
  - Flat-front propagation
- Time dependence
  - Transient
- Comparison
  - Method of Characteristics

- Specific case not identified, yet

FF007 – Cryogenic Line Cooldown

- Brennan, Brentari, Smith, & Steward, 1966
- Dimensions
  - 1D solution
  - 1D geometry
- Physics
  - Fluid flow
  - Convection
  - Phase change
  - Cryogenic fluids
- Time dependence
  - Transient



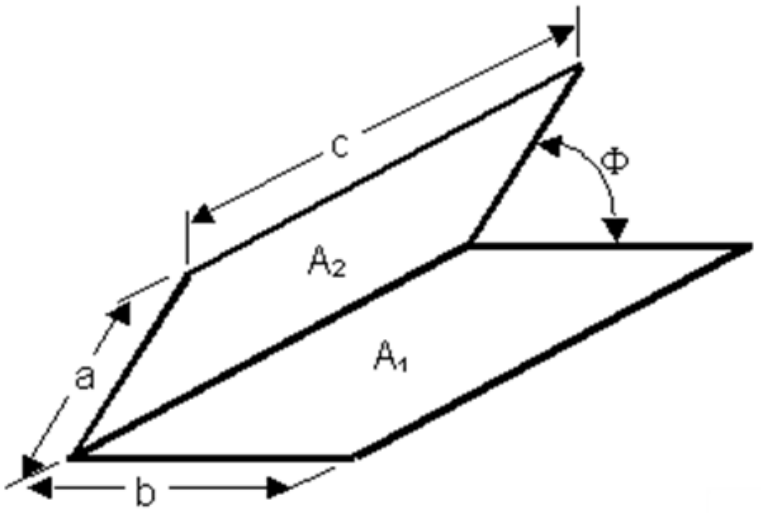
RADIATION CALCULATION CASES

RC001 – Non-Grey Radiation

- Howell, Menguc, & Siegel, Thermal Radiation Heat Transfer, 6th Edition, 2016
- Physics
  - Variable properties
  - Radiation
- Boundary conditions
  - Temperature
- Time dependence
  - Steady state
- Comparison
  - Closed-form solution

RCxxx – Radiation View Factors

- Howell, *A Catalog of Radiation Heat Transfer Configuration Factors*, 2018
  - Many configuration factors are cataloged with closed-form solutions
- Physics
  - Radiation
- Comparison
  - Closed-form solution



CONCLUSIONS

Conclusions

- A set of candidate benchmark cases has been presented
  - Compatible with thermal and fluid analysis software
  - Addresses needs of active and passive thermal designs
  - The set is incomplete
- CRTech is adding newly discovered benchmark cases to its current set of test cases
- NESC and the TFAWS community should consider standardizing a set of benchmark cases
  - CRTech will include any standardized benchmarks in testing

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