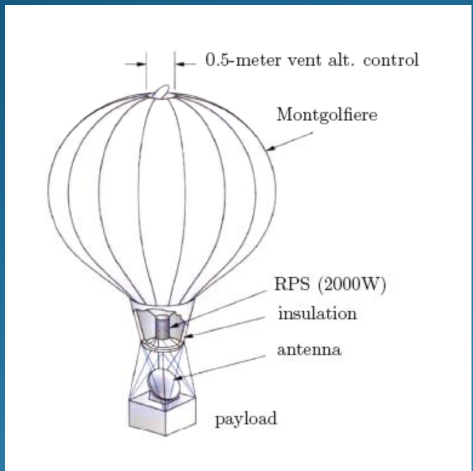

Computational Modeling and Experiments of Natural Convection for a Titan Montgolfiere

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Julian Nott, Nott Technology LLC
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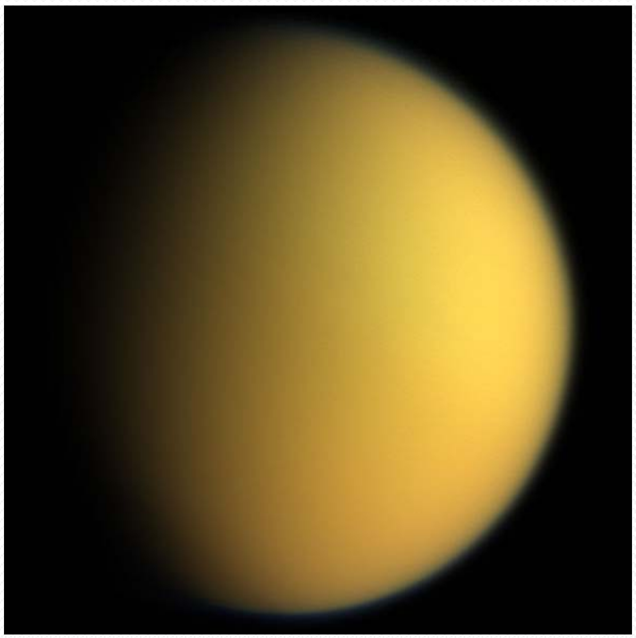
Titan's atmosphere

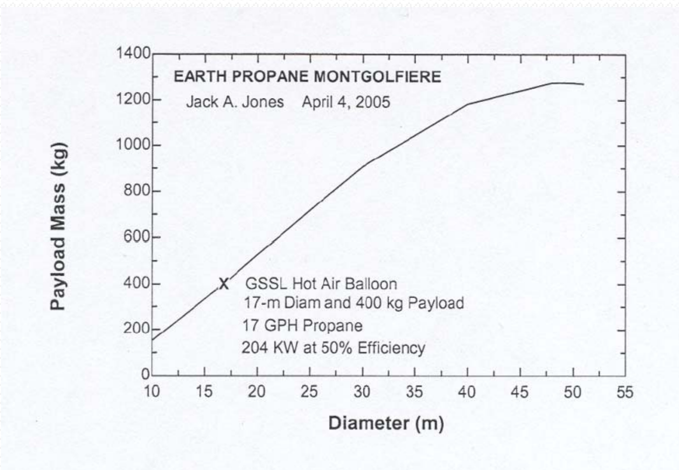


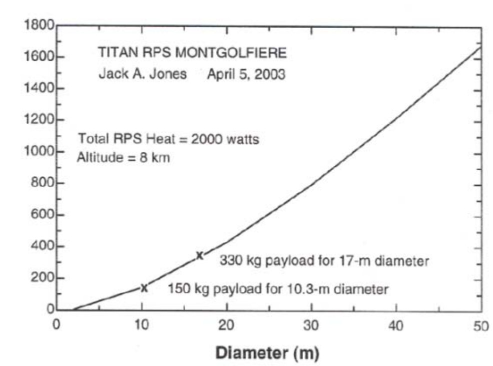
Parameter	Earth	Titan
temperature	298 K	83 K
density	1.2 kg/m^3	3.6 kg/m^3
pressure	1.0 atm	0.9 atm
viscosity	18.3 μPa s	6.0 μPa s
gravitational acceleration	9.8 m/s^2	1.4 m/s^2
composition	mainly N_2, O_2, H_2O, Ar	mainly N_2, CH_4, C_2H_6

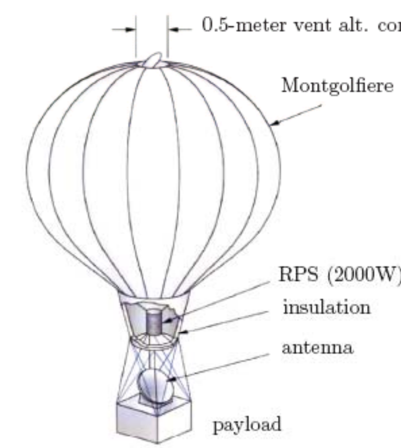
Titan Montgolfiere

- Titan: Cold (83 K), dense (3.6 kg/m^3), low gravity (g=1.4 m/s^2)
- Low temperature → radiation relatively unimportant compared to natural convection.
- GOOD NEWS: ~ 100 times less power than floating a comparable payload on Earth

Joseph and Jacques-Ètienne Montgolfier 1783







Objectives

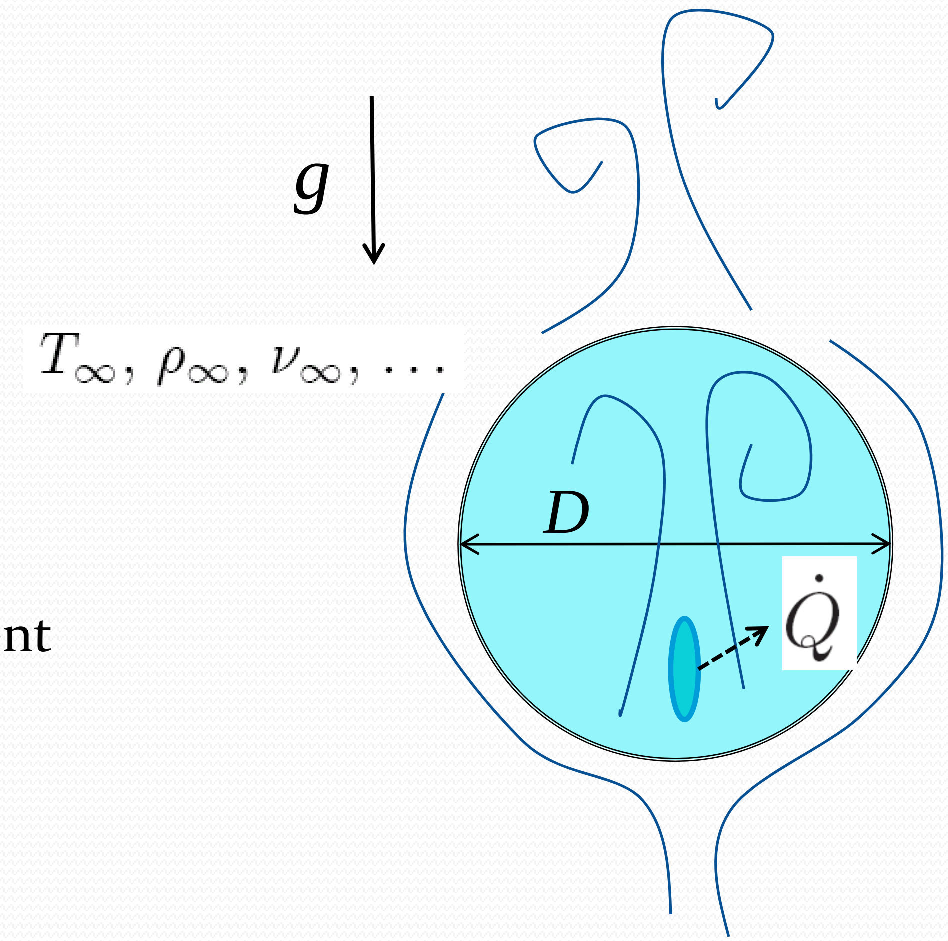
- Accurate predictions of buoyancy (lift) allow for maximal science payload, minize risk, cost, etc.
- Assess critical mission phases such as initial descent in Titan atmosphere
- Explore using CFD to investigate convection flow physics
  - Understand scaling of heat source strength and buoyancy
  - Validate/calibrate JPL system level models
  - Compare with model-scale experiments
  - Assess the efficacy of double-walled designs

Outline

- Modeling simplifications and natural convection theory
- Simulations
- Experiments
- Conclusions and future work

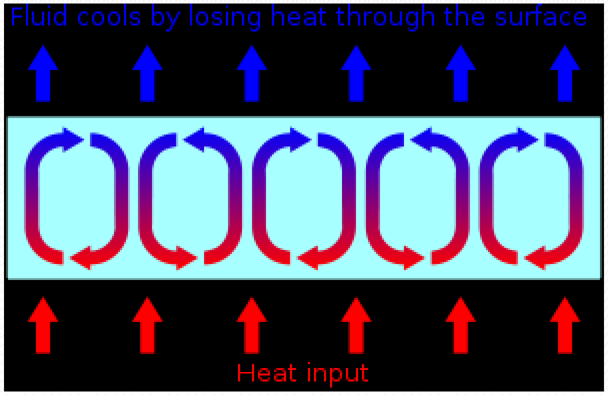
Modeling (1)

- Neglect radiation
- Stationary (for now)
- Thin membrane
- Boussinesq
  - Low temperature diff.
  - Incompressible flow
- Axisymmetric flow
  - In averaged sense for turbulent flow



$$W + \overbrace{F_d}^{\approx 0} = F_b \qquad F_b = \int (\rho_\infty - \rho)\, g dV \approx \rho_\infty g \int \left(\frac{T - T_\infty}{T_\infty}\right) dV$$

Natural convection: cells, thermals



$$\mathrm{Ra} = \frac{g\beta\left(T - T_{\infty}\right)L^{3}}{\nu\alpha}$$

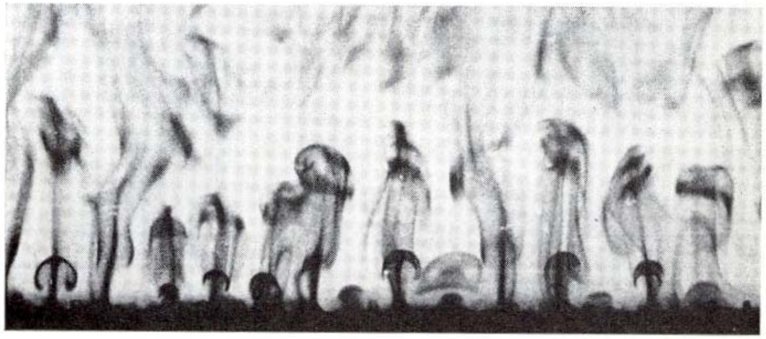
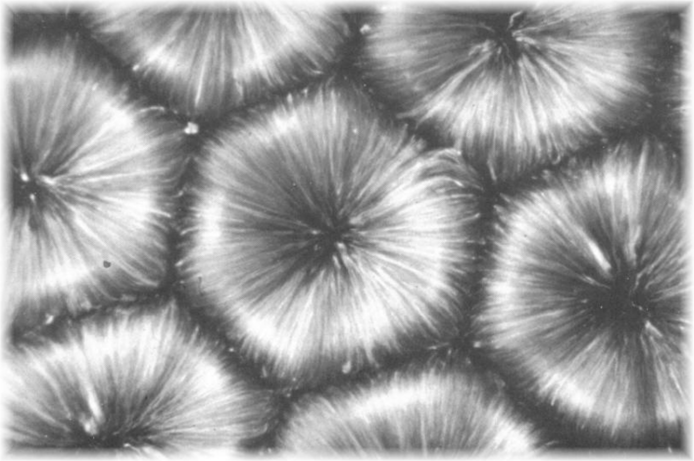


Fig. 7.14. 'Thermals' rising from a heated horizontal boundary under a layer of water. (From Sparrow, Husar and Goldstein 1970.)



Spherical Gap: movie

Modeling (2)

- Dimensional analysis: Minimize number of computations, provide scaling arguments for experiments/design.
- Example: steady state

$$\tilde{Q} = \frac{g D^2 \dot{Q}}{\rho_\infty c_p T_\infty \nu^3} \qquad \tilde{B} = \frac{6 F_b}{\pi \rho_\infty \nu^2}$$

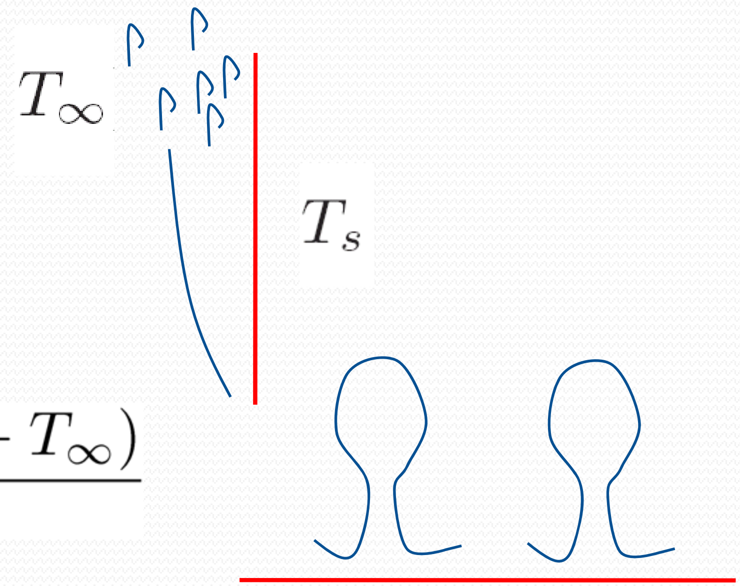
$$\tilde{B} = \mathrm{fun}\left(\tilde{Q}, \text{balloon geometry}\right)$$

  - Low Q: laminar convection
  - High Q: turbulent convection

Theory: heat transfer coefficients

$$\dot{q}'' = h\left(T_s - T_\infty\right)$$

$$\dot{Q} = A_s h_{avg}\left(T_{s\,avg} - T_\infty\right)$$

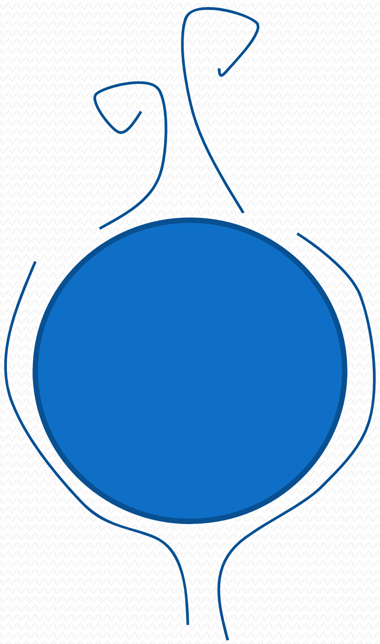


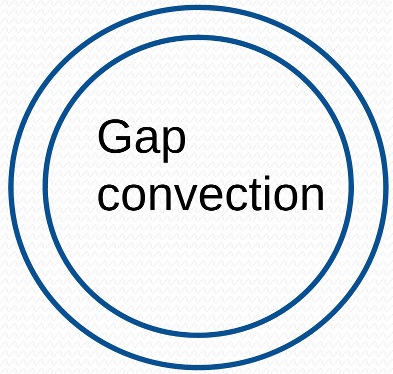
$$\mathrm{Nu} = \frac{h_{avg} L}{k} \qquad \mathrm{Ra} = \frac{g\beta\left(T_{avg} - T_\infty\right)}{\nu\alpha}$$

$$\mathrm{Nu} = \mathrm{fun}\left(\mathrm{Ra}, \mathrm{Pr}, \mathrm{geometry}, \mathrm{surface\ conditions}\right)$$

- Usually follow power-law behavior at high Ra
- Laminar: correlations from laminar boundary layer theory and/or empirical
- Turbulent: empirical correlations

Relevant correlations





$$\mathrm{Nu}_{Di \to Do} = 0.617 \left(\frac{1-\phi}{\phi \left(1+\phi^{7/5}\right)^{5}} \right)^{0.25} \mathrm{Ra}_{Di \to Do}^{0.25},$$

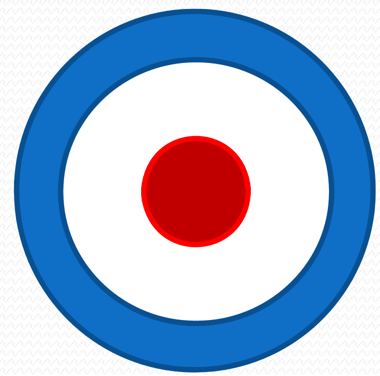
Raithby & Hollands1975

$$\phi = D_i / D_o$$

External convection

$$\mathrm{Nu}_{Do \to \infty} = \begin{cases} 2 + 0.6\mathrm{Ra}_{Do \to \infty}^{0.25} & \mathrm{Ra} < 1.5 \times 10^{8}, \\ 0.1\mathrm{Ra}_{Do \to \infty}^{0.340} & \mathrm{Ra} \geq 1.5 \times 10^{8}, \end{cases}$$

Campo 1980

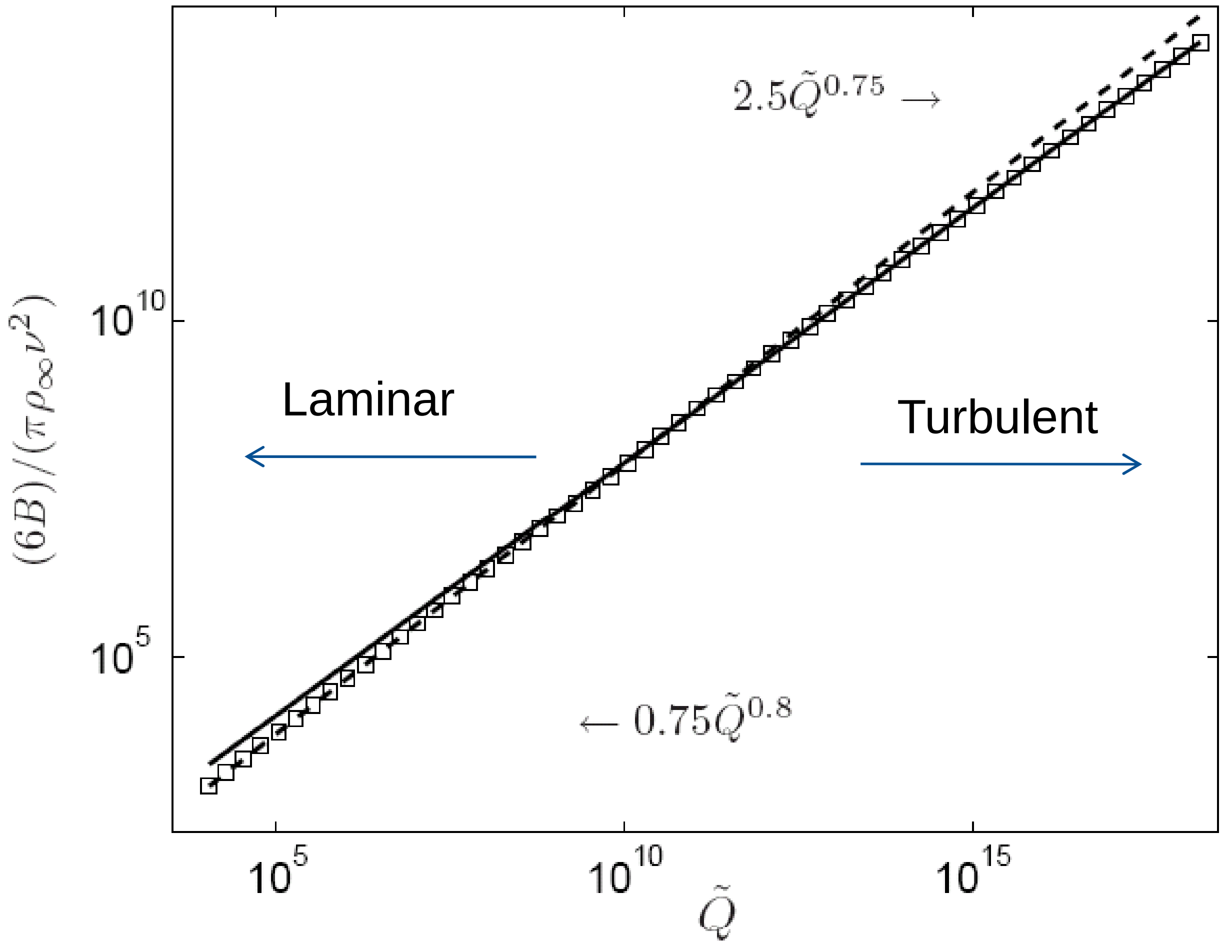


Internal convection

$$\mathrm{Nu}_{b \to s} = \begin{cases} 2.5 \left(2 + 0.6\mathrm{Ra}_{b \to s}^{0.333}\right) & \mathrm{Ra} < 1.35 \times 10^{8}, \\ 0.325\mathrm{Ra}_{b \to s} & \mathrm{Ra} \geq 1.35 \times 10^{8} \end{cases}$$

Horn 1983

Composite correlation



- Spherical, single-walled balloon based on internal/external correlations

Sources of uncertainty

- Modeling
  - Spherical vs. other balloon shapes
  - Internal convection problem: where was heat source?
  - Nonuniform temperature and/or heat flux at surface
- Turbulent flow
  - Data from different experiments
  - Sensitivity to boundary conditions, external sources of noise, etc.

Simulation Strategy

- Cover both laminar and turbulent regimes
- Laminar
  - Not (much) applicable to Titan Montgolfiere
  - But…assess modeling uncertainties while eliminating uncertainties associated with turbulence models
- Turbulent flow
  - Validate with experimental data

Simulation methods

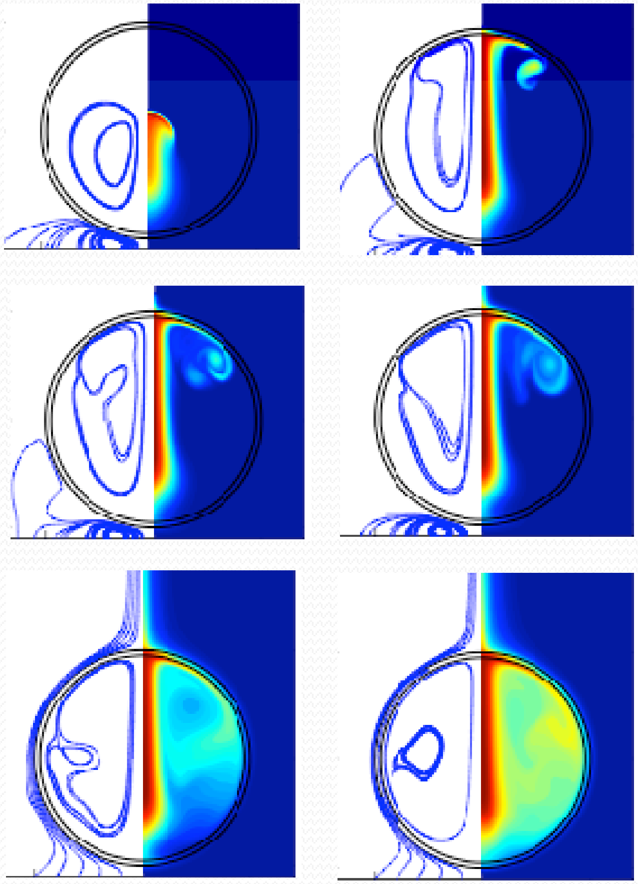
Laminar flow

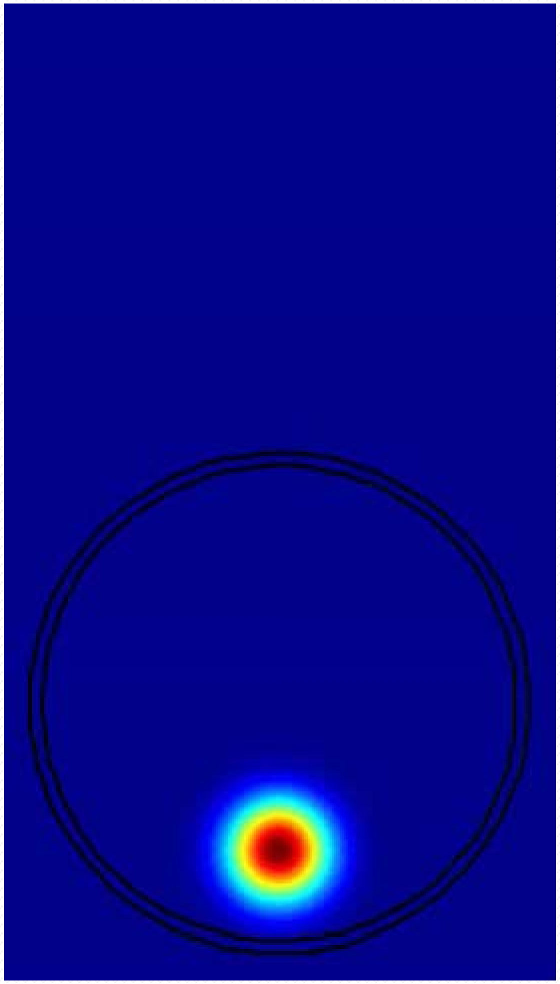
- In-house incompressible CFD code
- Immersed boundary method (arbitrary geometry)
- 2^{nd}-order staggered mesh FV scheme
- Detailed validation and convergence cases

Turbulent Flow

- Fluent Commercial CFD code
- Turbulence modeling
  - Reynolds Averaged Navier-Stokes equations
  - Steady state, time-averaged flow field
  - k-ε turbulence model (other models available)

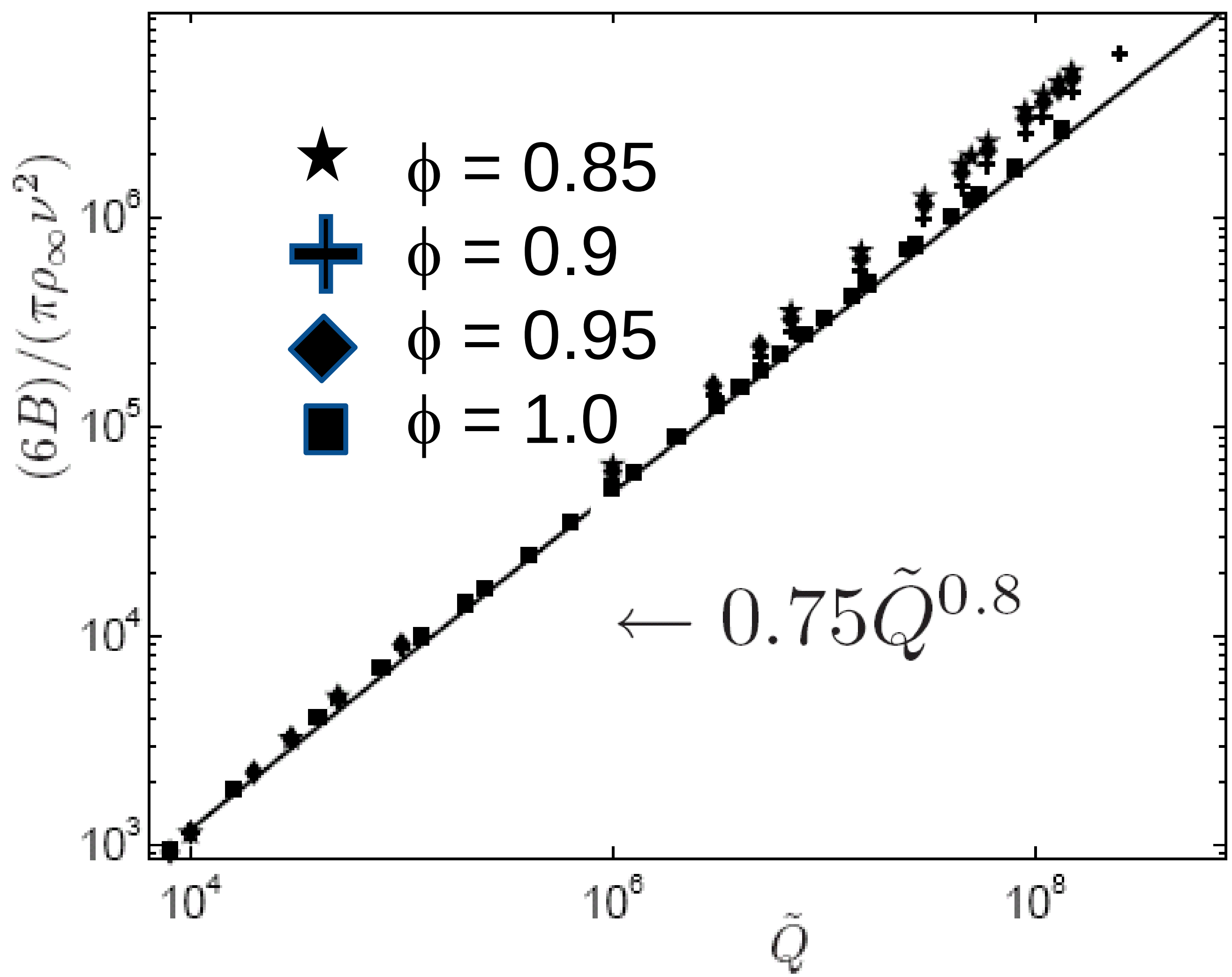
Typical laminar flow/temperature distribution



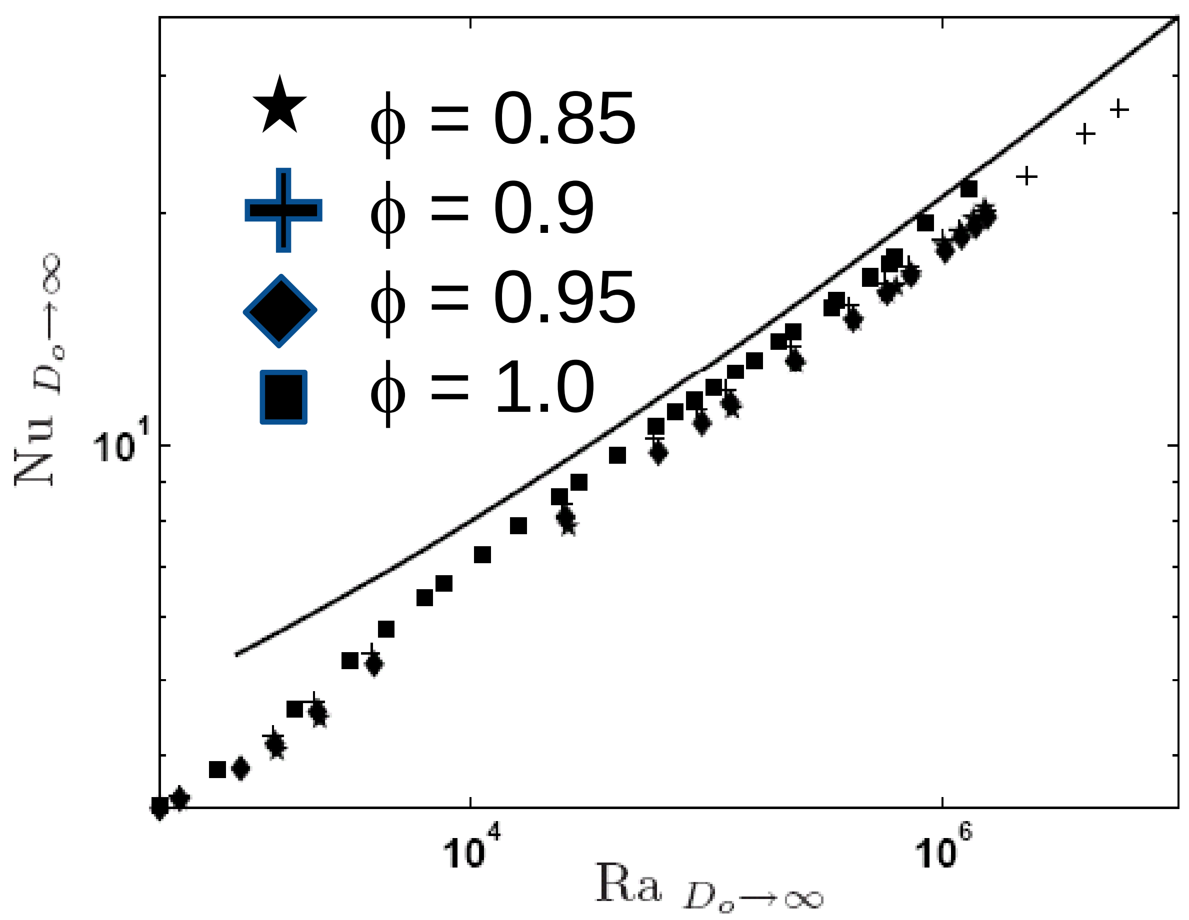


$\phi = 0.95$

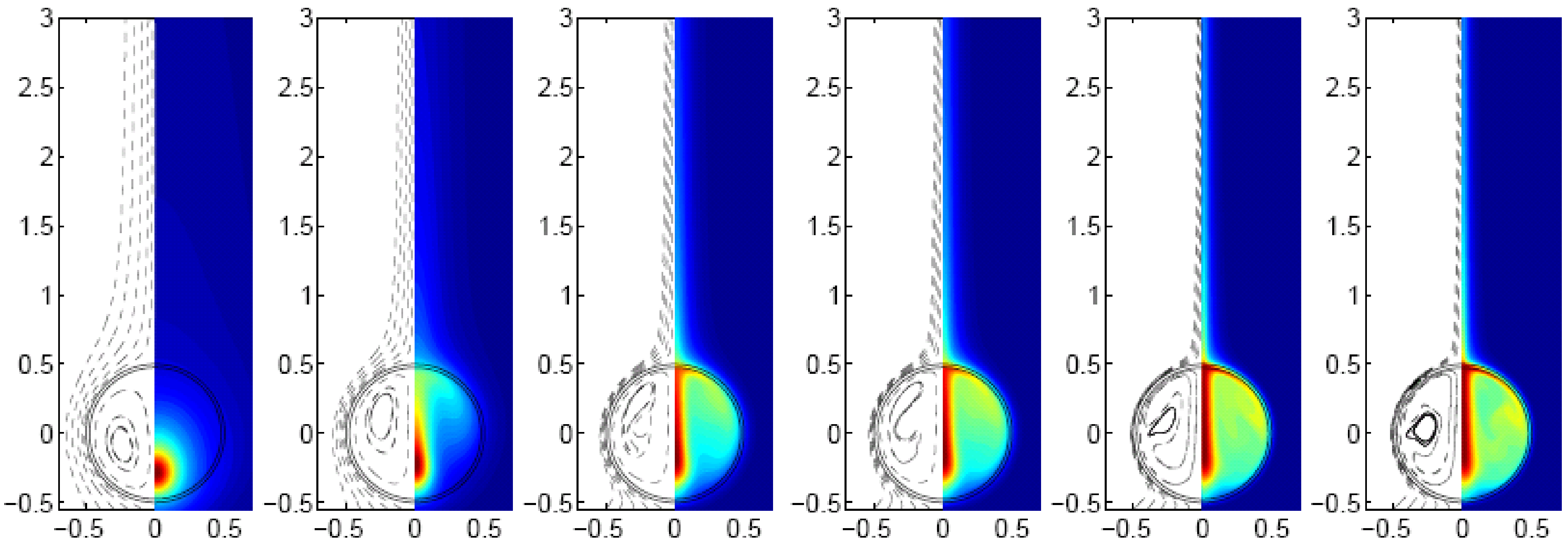
Laminar steady-state results



External correlation



Flow/temperature distribution



10^4 10^6 6×10^6 15×10^7 4×10^9 8×10^9

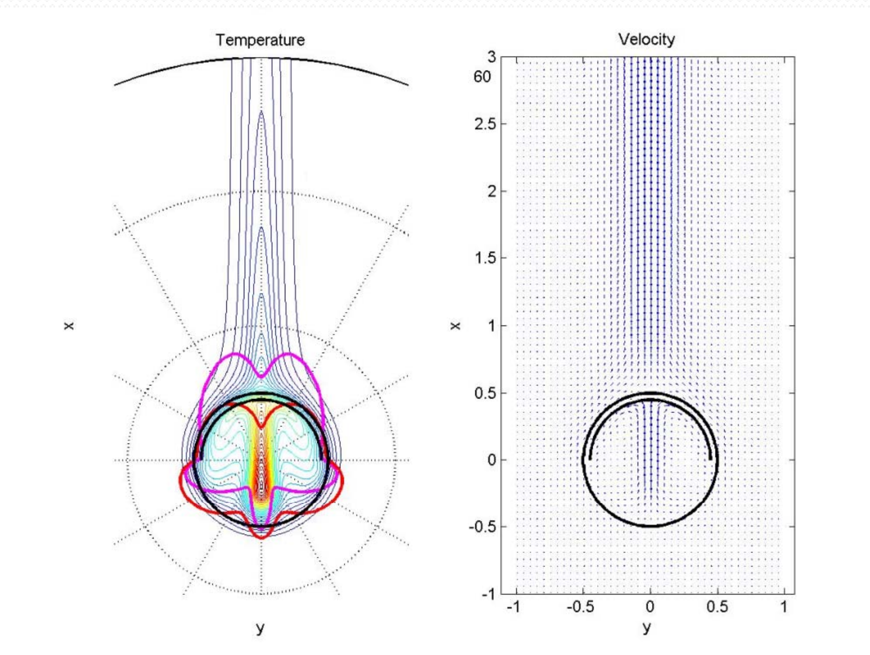
$\phi = 0.95$

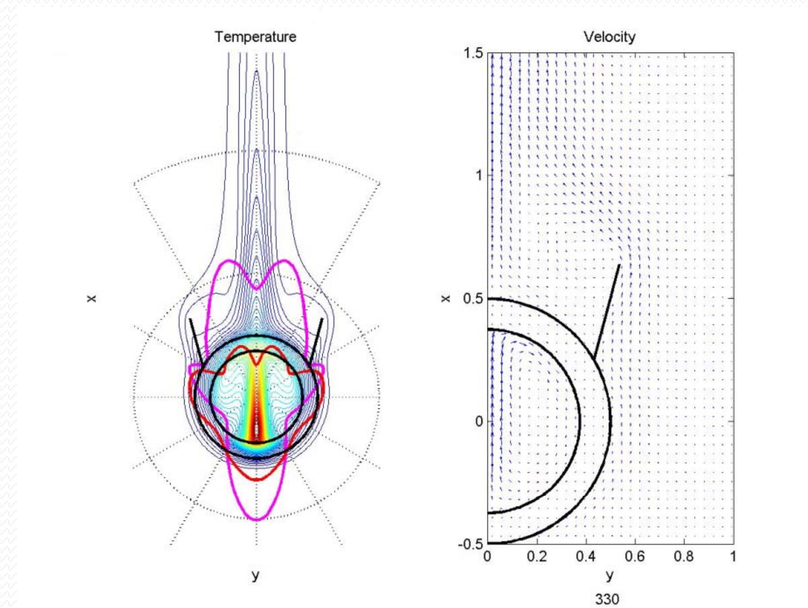
Summary of laminar results

- Confirms efficacy of double-walled designs
- Overall very reasonable comparison with composite correlation for single-walled balloons
- No satisfactory theory including gap effect (though gap Rayleigh number very low in simulations)
- Evidence of temperature non-uniformity being responsible for differences in internal/external correlations (~25% changes in buoyancy)

Double wall is good…can we do better?

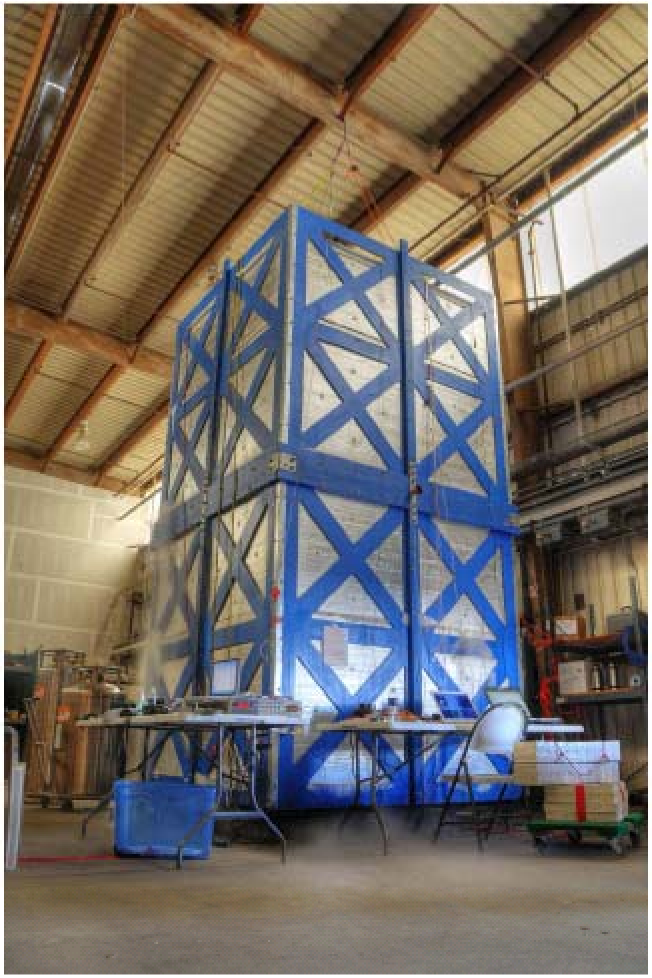
- Best we could is reduce all currents in the balloon (no vonection, conduction only)
- Can we use interior/exterior baffling to approach these conditions?





Experiments: Titan Sky Simulator™

- 2.5 m x 2.5 m x 5 m
- Filled with liquid N_2
- Internal fans and baffling to ensure
  - Uniform ambient conditions around balloon
  - Minimize wind
- Resistance heater with relatively large surface area
- Balloon tethered to scale



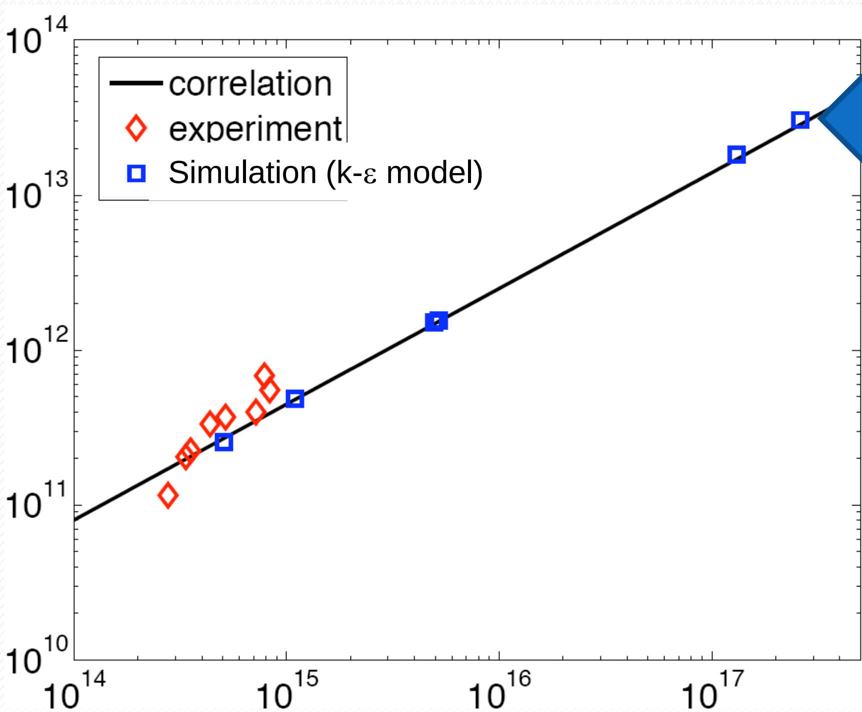
Balloon flying at 103K

24 Thermocouples

Q [w]	T_∞ [K]	gB [Kg]
198	103	0.304 (35)
422	158	0.327 (14)
422	136	0.453 (41)
422	144	0.561 (83)
195	120	0.274 (38)
195	148	0.184 (9)
195	156	0.168 (3)
195	189	0.095 (33)

Comparison of theory, experiment and (turbulent) simulation

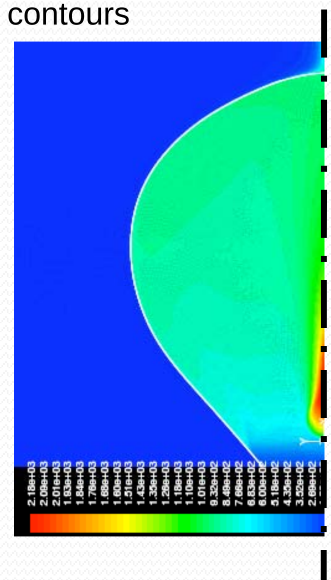
Scaled buoyancy (lift force) versus scaled heat input



$$\frac{gD^2\dot{Q}}{\rho c_p T_\infty \nu_\infty^3}$$

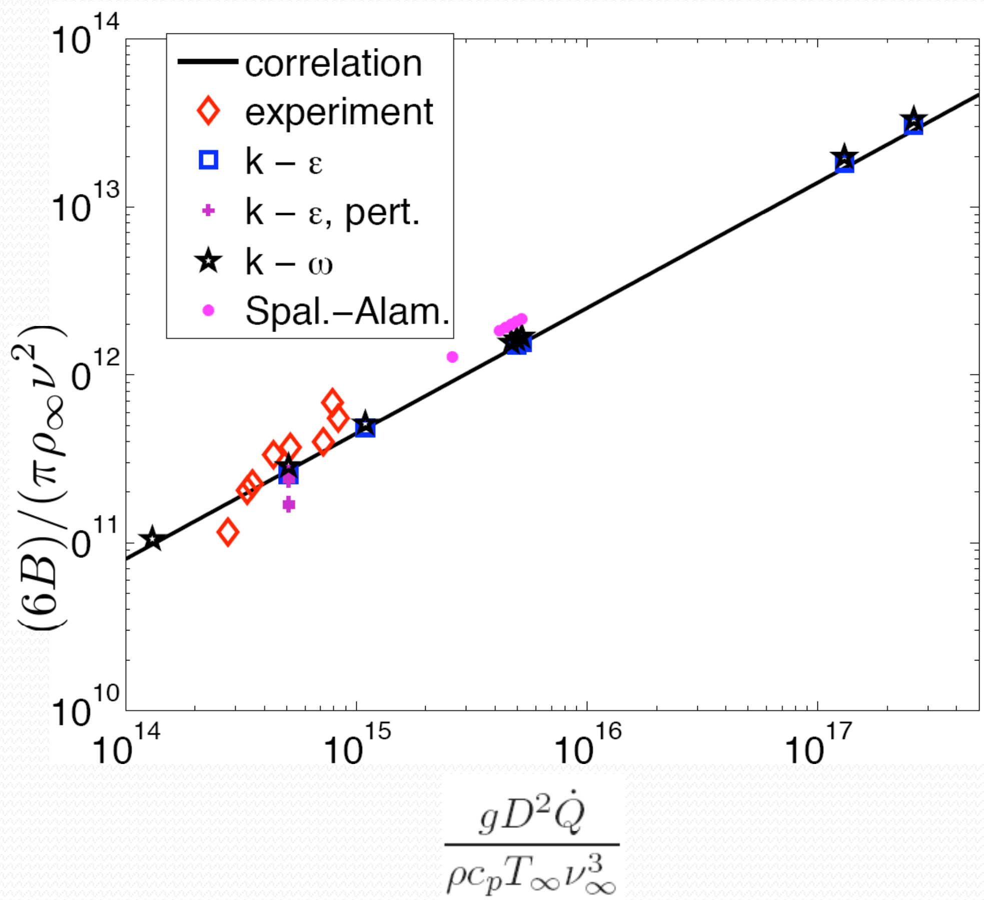
Heat input = 2kW
D = 9 m
@ Titan atmos
(T_∞=83k)
Predicted load:
B/g = 176 kg

Predicted temperature contours



Sensitivity of the predicted lift force to the turbulence model was evaluated

- Different turbulence models give greater buoyancy than correlation (correlation is conservative)
- k-ε model closest to empirical correlation
- Perturbed model constants yield poorer agreement with correlation



Summary of turbulent results

- Respectable agreement between experiments, simulations, and engineering correlations

Thanks!