# CMS Pixel Cooling with $CO_2$

## Preliminary Two-phase Flow Modeling

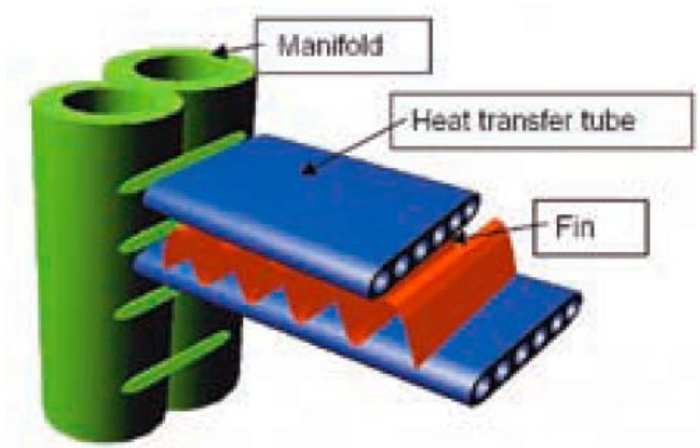
Terry Tope - 10.7.08

# $CO_2$ Literature Search

- Looked at 30+ journal papers
- Existing hydrofluorocarbon (HFC) refrigerants have global warming concerns - may be phased out
- Researchers investigating $CO_2$ for “comfort cooling” applications last 10 years
- Initial $CO_2$ systems less efficient than R22, R134a, and R410A systems
- Researchers looking for cycle improvements

# $CO_2$ Literature Search

- Evaporator design in particular is of interest to researchers (and CMS)
  - Micro-channel tubes typical configuration
  - Significant amount of experimental data



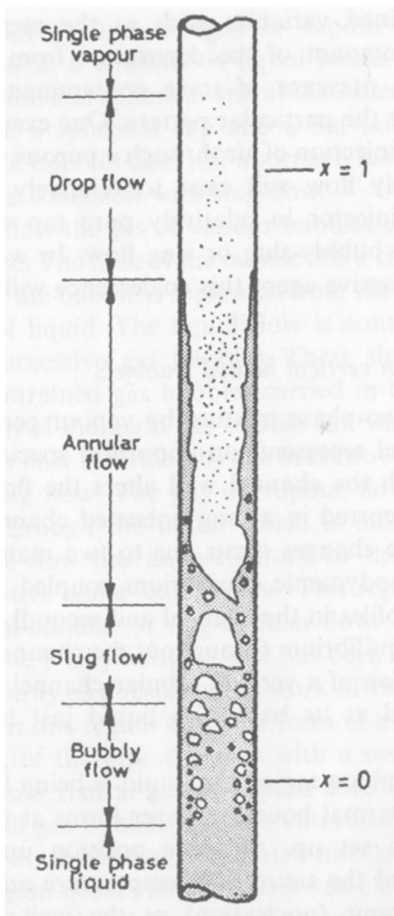
# $CO_2$ Literature Search

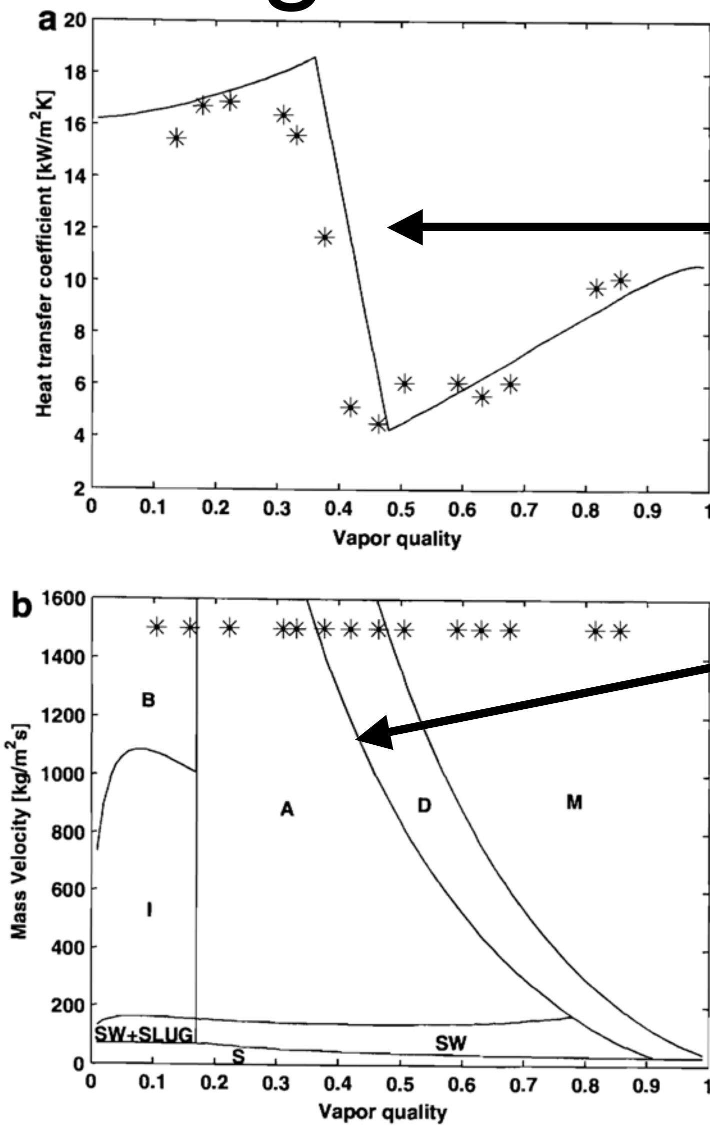
- Existing two-phase correlations work poorly based on experimental results
  - High vapor density, very low surface tension (10x), high vapor viscosity, low liquid viscosity compared to HFCs
  - $CO_2$ film coefficient 2-3x greater (good!)
  - $CO_2$ dryout at much lower vapor qualities (bad!)

# $CO_2$ Literature Search

- Two papers from J.R. Thome in 2008
- Updated past models based on entire $CO_2$ database in the open literature
  - Flow regime map correlations
  - Heat transfer correlations
  - Pressure drop correlations
- Currently best predictive models, still ~25% error which is typical for two-phase flow correlations applicable over a wide range

# Flow Regime Example




Film coefficient drops in dryout regime - avoid!

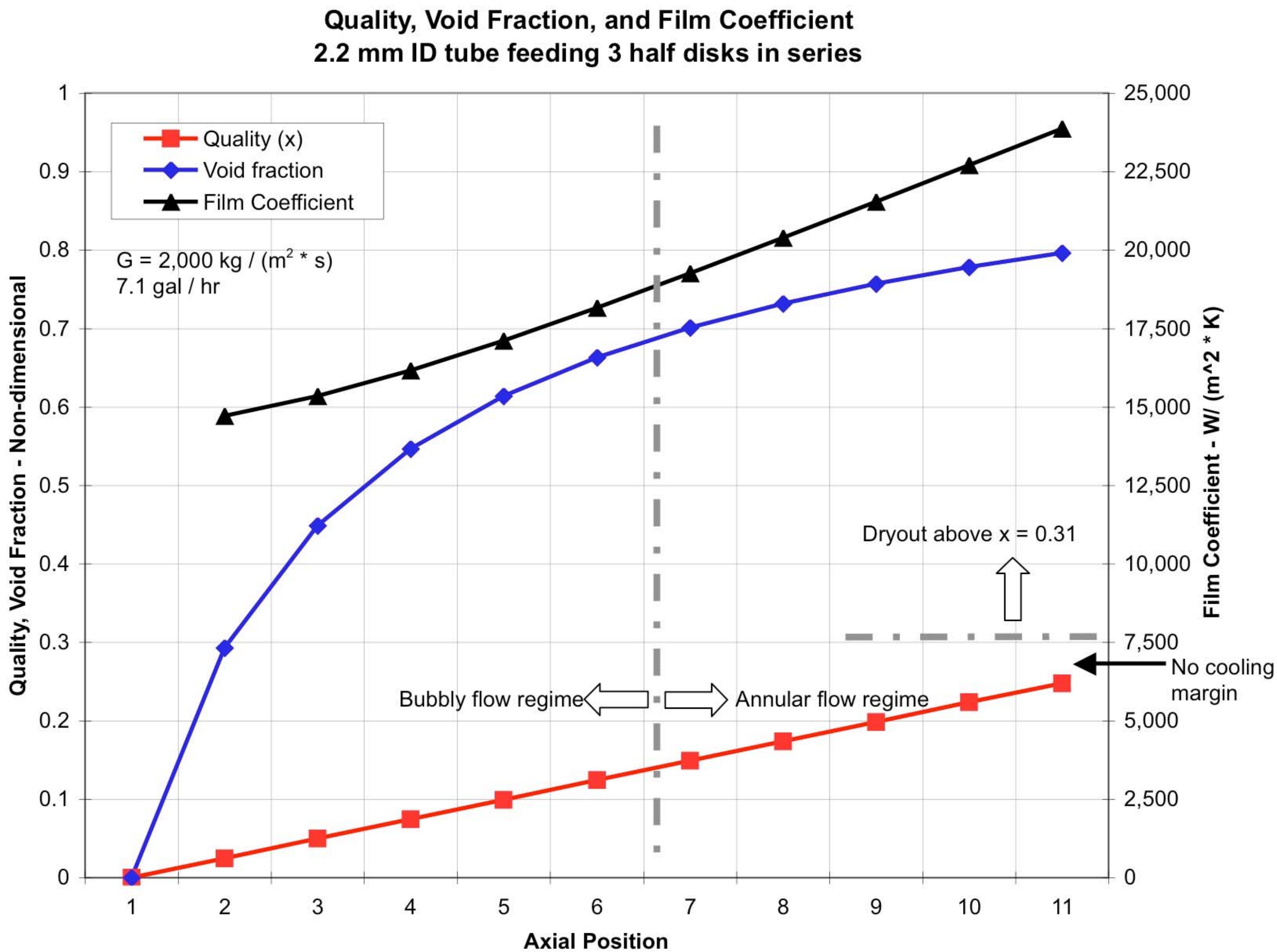
As the mass flux increases, dryout occurs at lower and lower vapor fractions

# Computer Model Developed

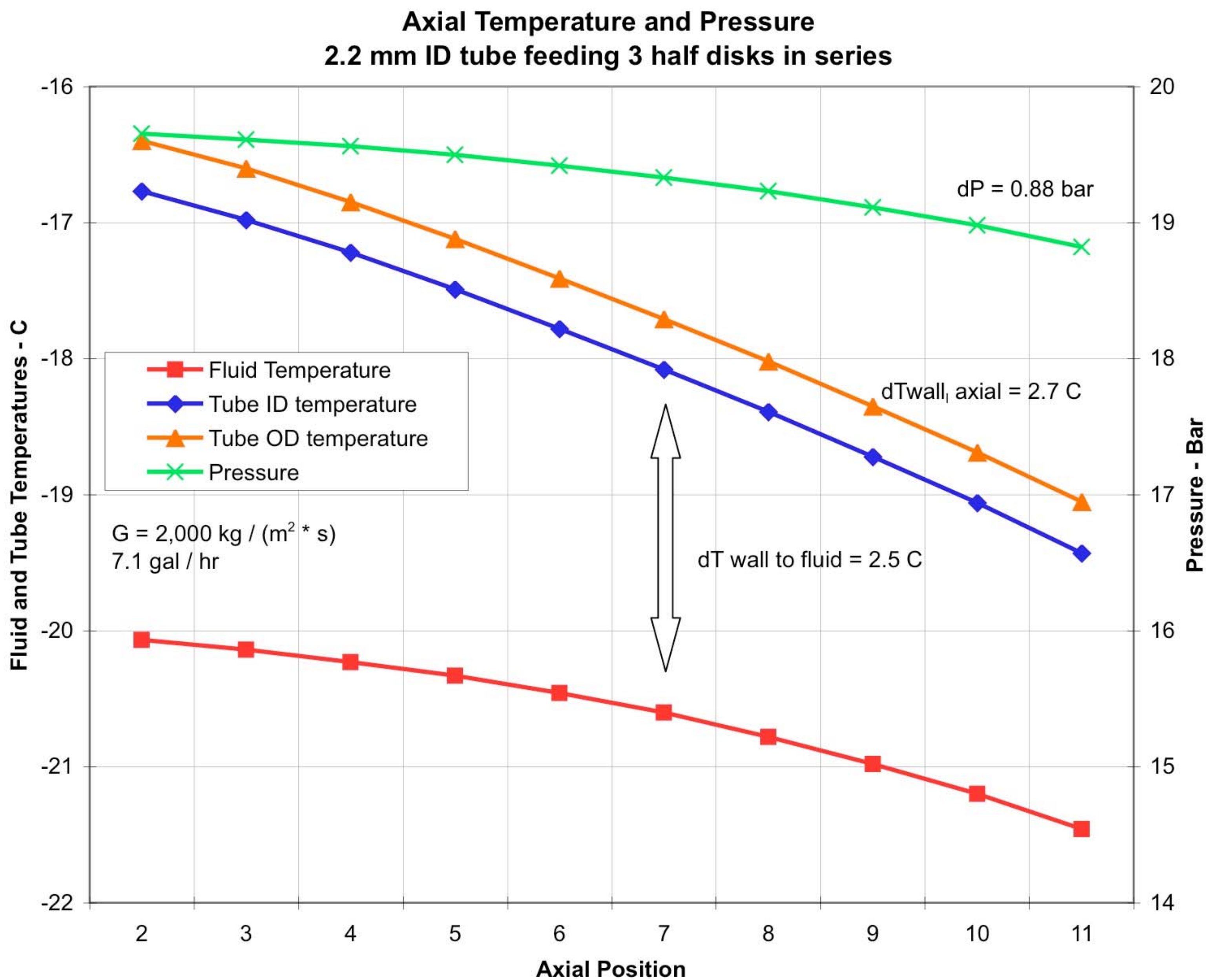
- Based on Thome's 2008 mechanistic correlations
- Used EES numerical solver which has all required $CO_2$ fluid properties built in
- Tube length divided into 10 computational sections to account for vapor growth and property variation
- Currently 563 equations! (of course that counts repeated equations)

# Model inputs

- One tube feeding 3 half disks in series
  - 15 W/blade, 12 blades per half disk, total 540 W
- Tube follows the OD of each half disk
- Smallest ID tube workable in the model
  - 2.4 mm OD / 2.21 mm ID SS tube from Eagle Stainless
  - We have some experience brazing very small tubing including capillary tubing using VCR connections
  - 329 bar max pressure per piping code for this tube size - $CO_2$ Psat @ 30 C is 72 bar

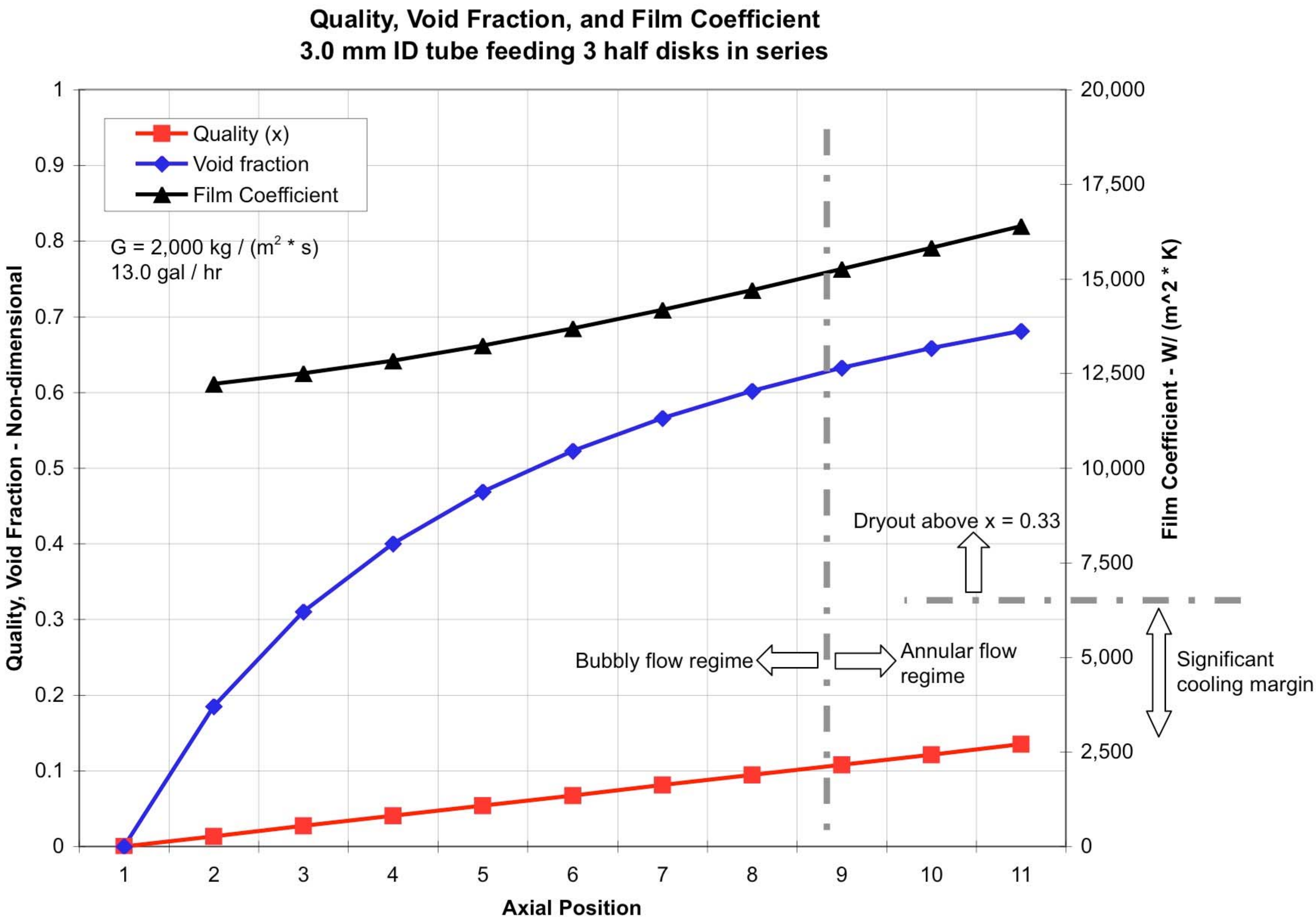


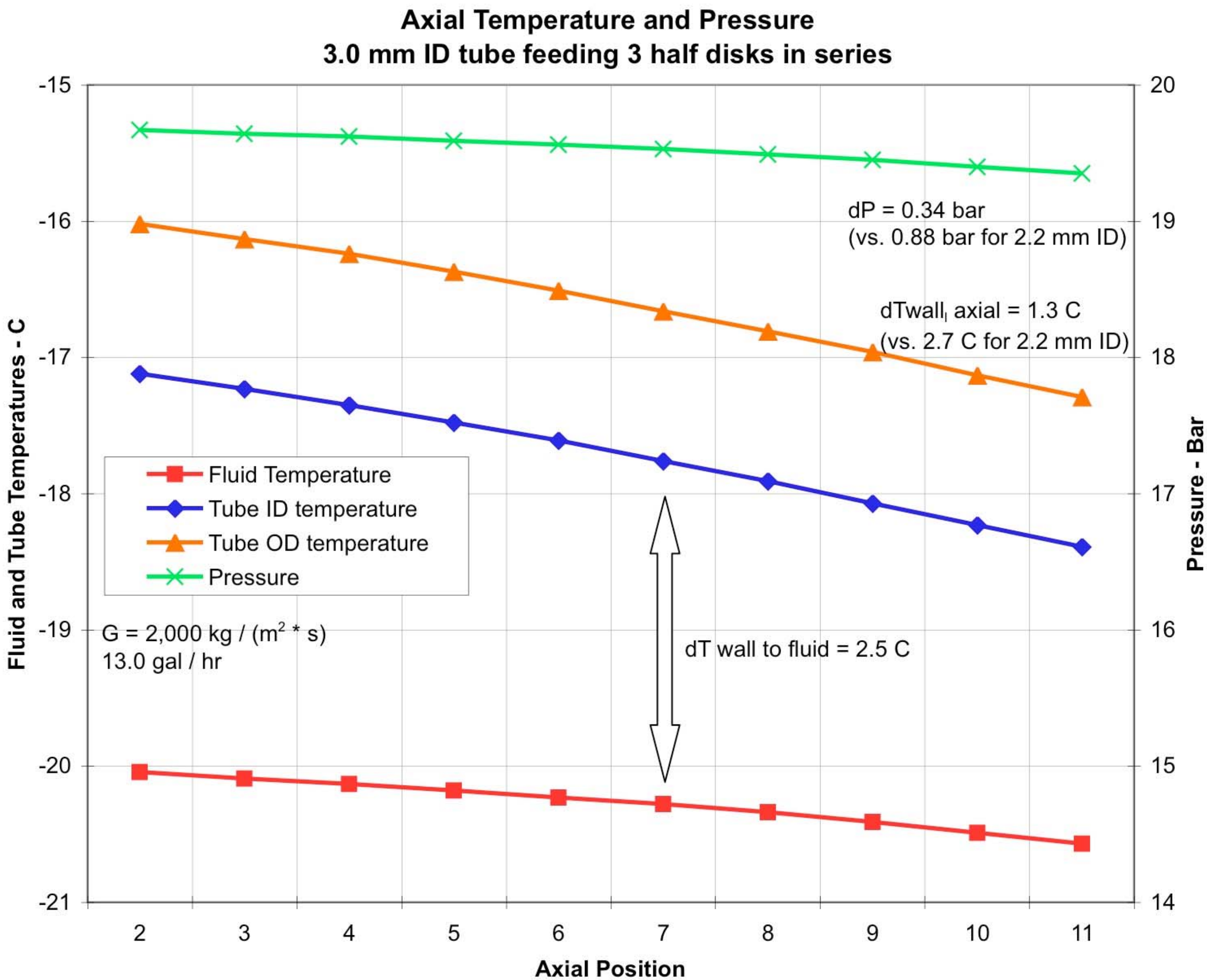
Quality, Void Fraction, and Film Coefficient
2.2 mm ID tube feeding 3 half disks in series
Quality (x)
Void fraction
Film Coefficient
G = 2,000 kg / (m² * s)
7.1 gal / hr
Dryout above x = 0.31
No cooling margin
Bubbly flow regime
Annular flow regime
Quality, Void Fraction - Non-dimensional
Film Coefficient - W/ (m^2 * K)
Axial Position
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
25,000
22,500
20,000
17,500
15,000
12,500
10,000
7,500
5,000
2,500
0
1 2 3 4 5 6 7 8 9 10 11


Axial Temperature and Pressure
2.2 mm ID tube feeding 3 half disks in series
-16
-17
-18
-19
-20
-21
-22
20
19
18
17
16
15
14
2
3
4
5
6
7
8
9
10
11
Axial Position
Fluid and Tube Temperatures - C
Pressure - Bar
Fluid Temperature
Tube ID temperature
Tube OD temperature
Pressure
dP = 0.88 bar
dTwall$_i$ axial = 2.7 C
G = 2,000 kg / (m$^2$ * s)
7.1 gal / hr
dT wall to fluid = 2.5 C

# Computer model

- Typically we'd design a cooling system with larger safety margins
- Would not consider a tube near dryout like the 2.2 mm ID tube
- Rigorous thermal testing would be required to use such a tube
- What kind of margin are we comfortable with?
- Next slides show a 3 mm ID / 3.76 mm OD tube (254 bar $P_{max}$) and its larger cooling margin


Quality, Void Fraction, and Film Coefficient
3.0 mm ID tube feeding 3 half disks in series
Quality (x)
Void fraction
Film Coefficient
G = 2,000 kg / (m^2 * s)
13.0 gal / hr
Quality, Void Fraction - Non-dimensional
Film Coefficient - W/ (m^2 * K)
Dryout above x = 0.33
Bubbly flow regime
Annular flow regime
Significant cooling margin
Axial Position
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2,500
5,000
7,500
10,000
12,500
15,000
17,500
20,000
1
2
3
4
5
6
7
8
9
10
11



Axial Temperature and Pressure
3.0 mm ID tube feeding 3 half disks in series
Fluid and Tube Temperatures - C
Pressure - Bar
Axial Position
-15
-16
-17
-18
-19
-20
-21
20
19
18
17
16
15
14
2
3
4
5
6
7
8
9
10
11
Fluid Temperature
Tube ID temperature
Tube OD temperature
Pressure
dP = 0.34 bar
(vs. 0.88 bar for 2.2 mm ID)
dTwall axial = 1.3 C
(vs. 2.7 C for 2.2 mm ID)
G = 2,000 kg / (m² * s)
13.0 gal / hr
dT wall to fluid = 2.5 C

# Future Work

- Verify computer model and optimize tube diameter, flow rate, inlet temperature
- Work with CM Lei to thermally link tube to blades
- Expand piping program to include supply/return tubing, pump, chiller, etc.
- Select components for flow tests at FNAL, chiller, pump, heat exchanger

# Issues/Questions

- Supply 16 mm OD / 50 ft. long Cu tube is only rated for a max $CO_2$ saturation pressure per B31.3 corresponding to 18 C.
- Do the supply/return tubes thermally communicate with the "180 tube bundle?"
- Must the pump and chiller be in the collision hall?