Optimum Column Design for Capacity and Efficiency

(Presented at: [100e]-Distillation Honors: Dale Nutter)

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Prepared for presentation at the AIChE Spring National Meeting
New Orleans, LA
Monday, April 26, 2004

1. **Capacity and Efficiency Performance**
2. **Capacity and Efficiency Models and Predictions**
3. **Examples**

Tray Capacity and Efficiency Performance

- Flooding Capacity
  - System limit
  - Jet flooding
  - Froth flooding
  - DC choke flooding
  - DC backup flooding
- Tray efficiency
  - Point efficiency
  - Tray liquid mixing pools
  - Murphree tray efficiency
  - Dry overall tray/column efficiency
  - Overall tray/column efficiency

Packing Capacity and Efficiency Performance

- Flooding Capacity
  - System limit
  - Flooding capacity
- Packing efficiency or HETP
  - HTU_{OG}, HTU_G, HTU_L
  - Mass transfer driving forces, non-ideal flow
  - HETP hump for structured packing
  - Effect of bed length
  - HETP

System Limit or Ultimate Capacity

Definition:

- Capacity factor is defined as vapor velocity multiplied the square root of the vapor density divided by the difference between liquid and vapor densities.

$$C_s = \frac{V_{load}}{A_s} = u_V \sqrt{\frac{\rho_V}{\rho_L - \rho_V}}$$

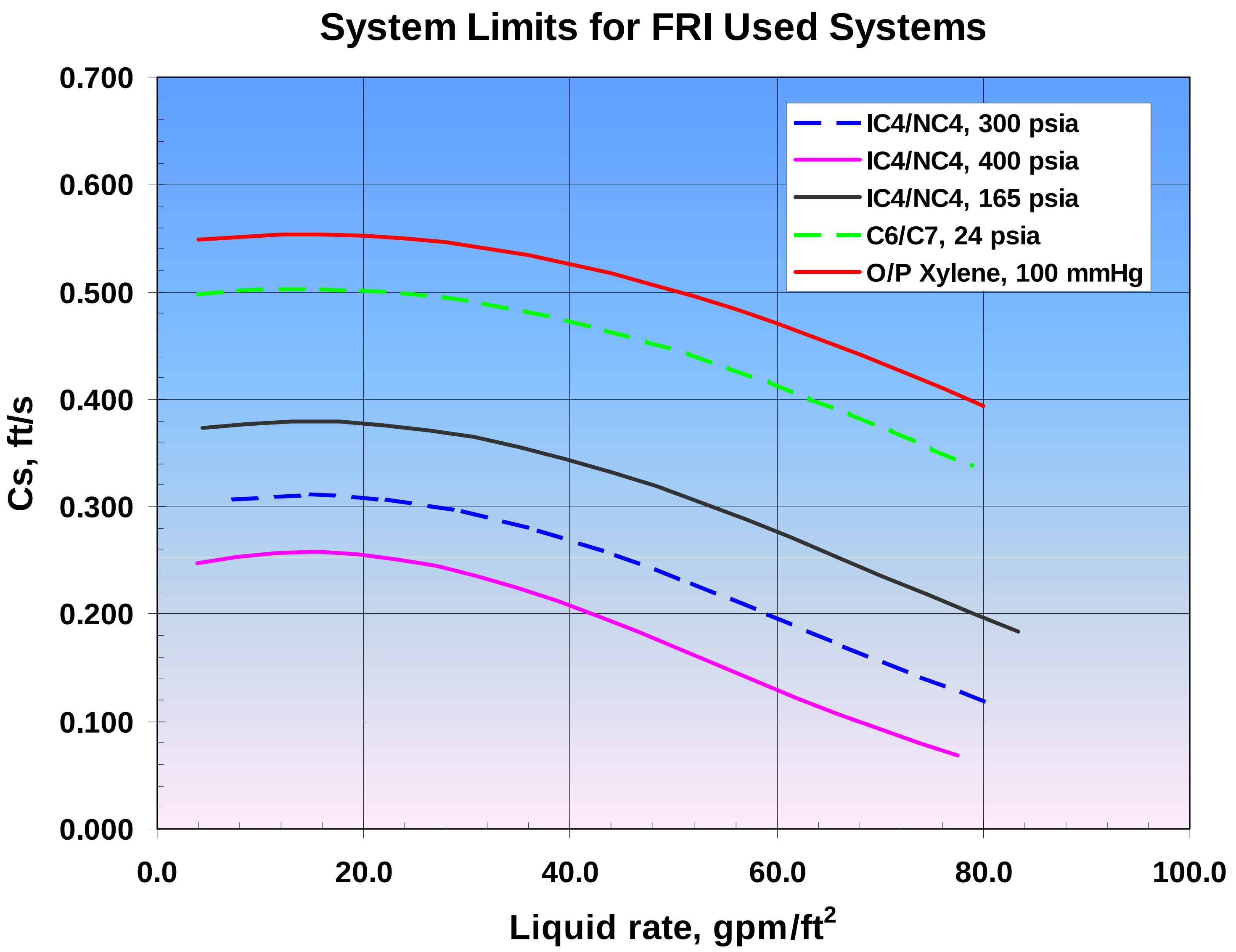
- A limiting combination of vapor and liquid loads which is a function of system properties only. If exceeded, massive entrainment occur. Conventional tray/packing capacity cannot exceed system limit.

System Limit or Ultimate Capacity

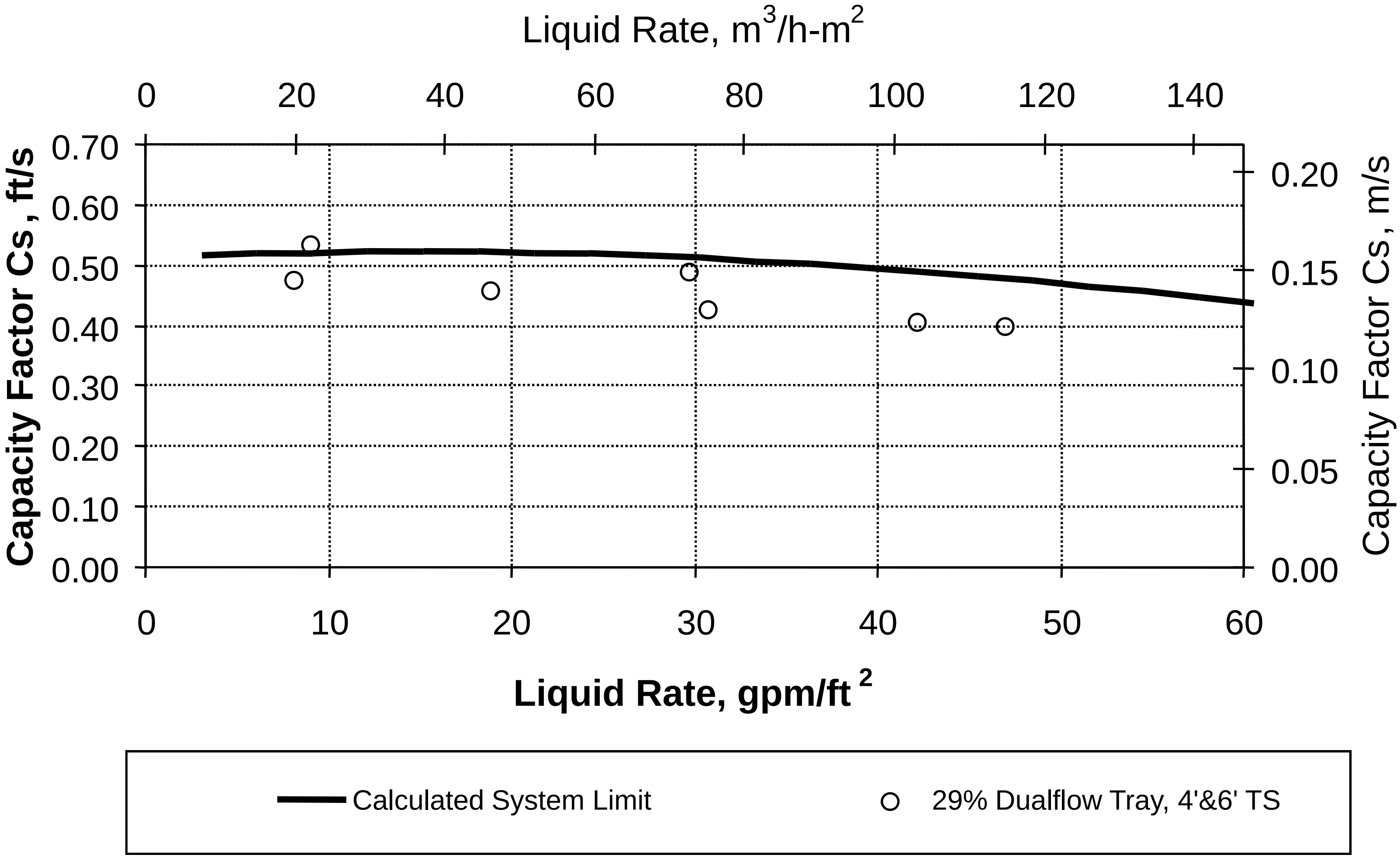
System Limit Model:

- FRI developed system limit model based on data obtained for trays and packings.
- System limit is only a function of system physical properties and is independent of hardware.
- The system limit is useful in determining the maximum capacity a column can possibly have.

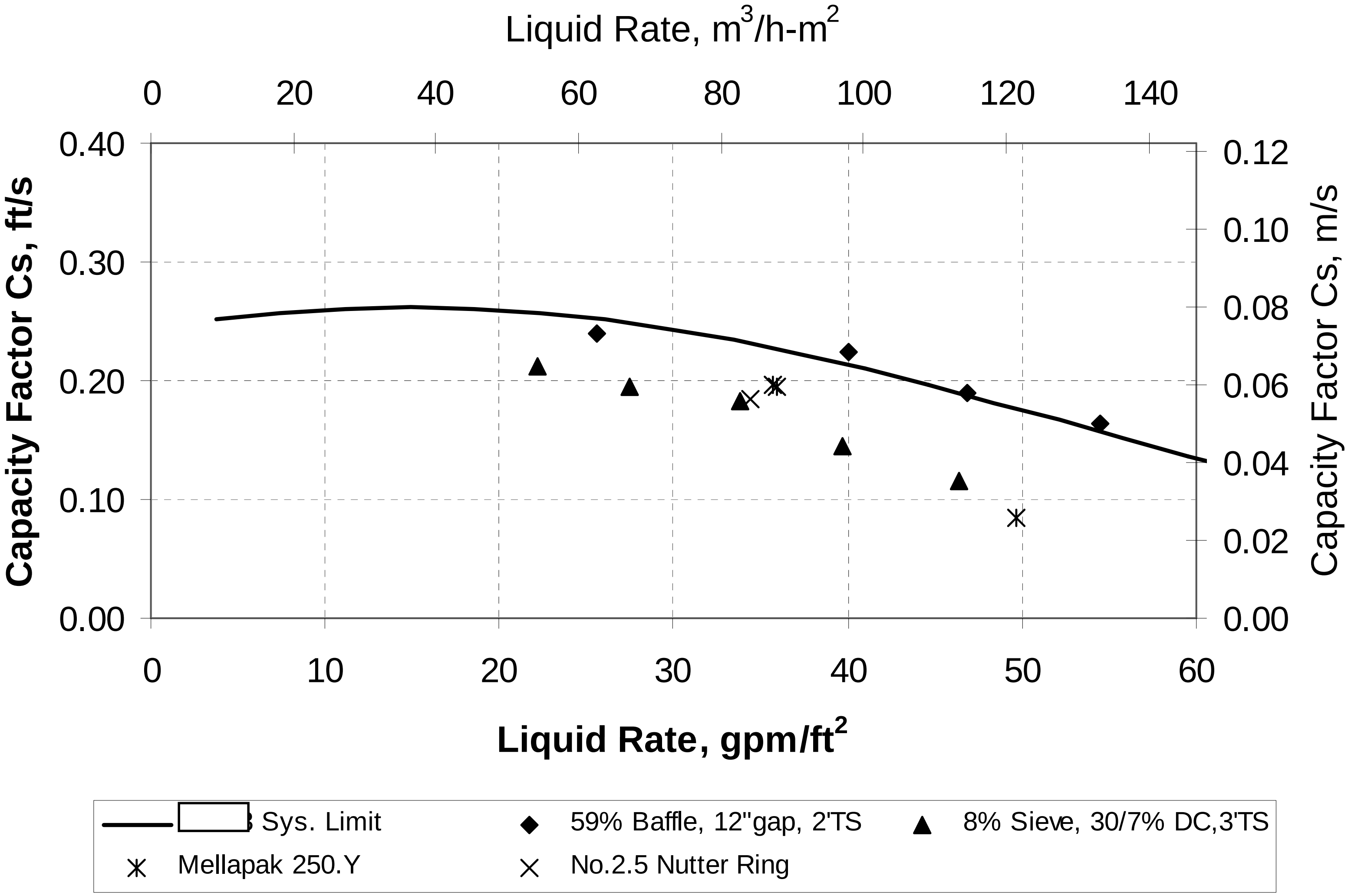
Simulated System Limit for Common Systems



System Limit for the O/P Xylene System at 240 mmHg



System Limit for the IC4/NC4 System at 400 psia



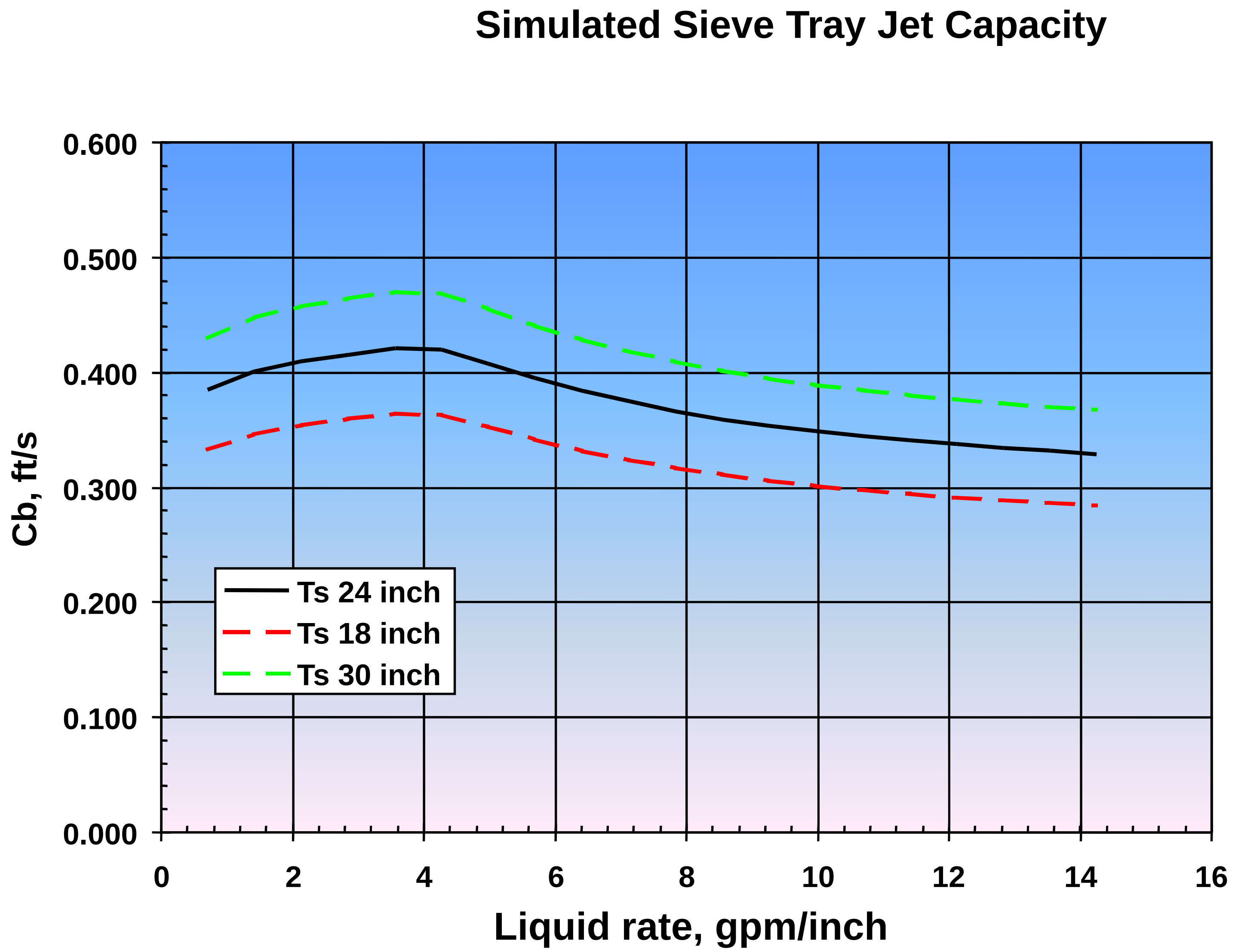
Tray Jet Flooding Capacity

- Jet flooding is due to massive entrainment of liquid to the tray above.
- FRI has developed empirical models for jet flood capacity.

Tray Jet Flooding Model Functional Analysis:

- Jet capacity increases as bubbling and free area increases.
- Jet capacity increases as tray spacing increases.
- Jet capacity increases as open area increases.
- Jet capacity increases as hole size decreases.
- Jet flooding often limits column capacity for low pressure and low liquid rate systems.

Jet capacity increases as tray spacing increases.



Tray DC Flooding Capacity

Definition:

- DC choke flood: flooding occurs when the downward velocity of froth is so high that little or no vapor disengagement occurs. It is determined by DC size.
- DC backup flood: Downcomer backup exceeds the tray spacing plus weir height, so that the froth backs up on the tray above. It is determined by DC depth.

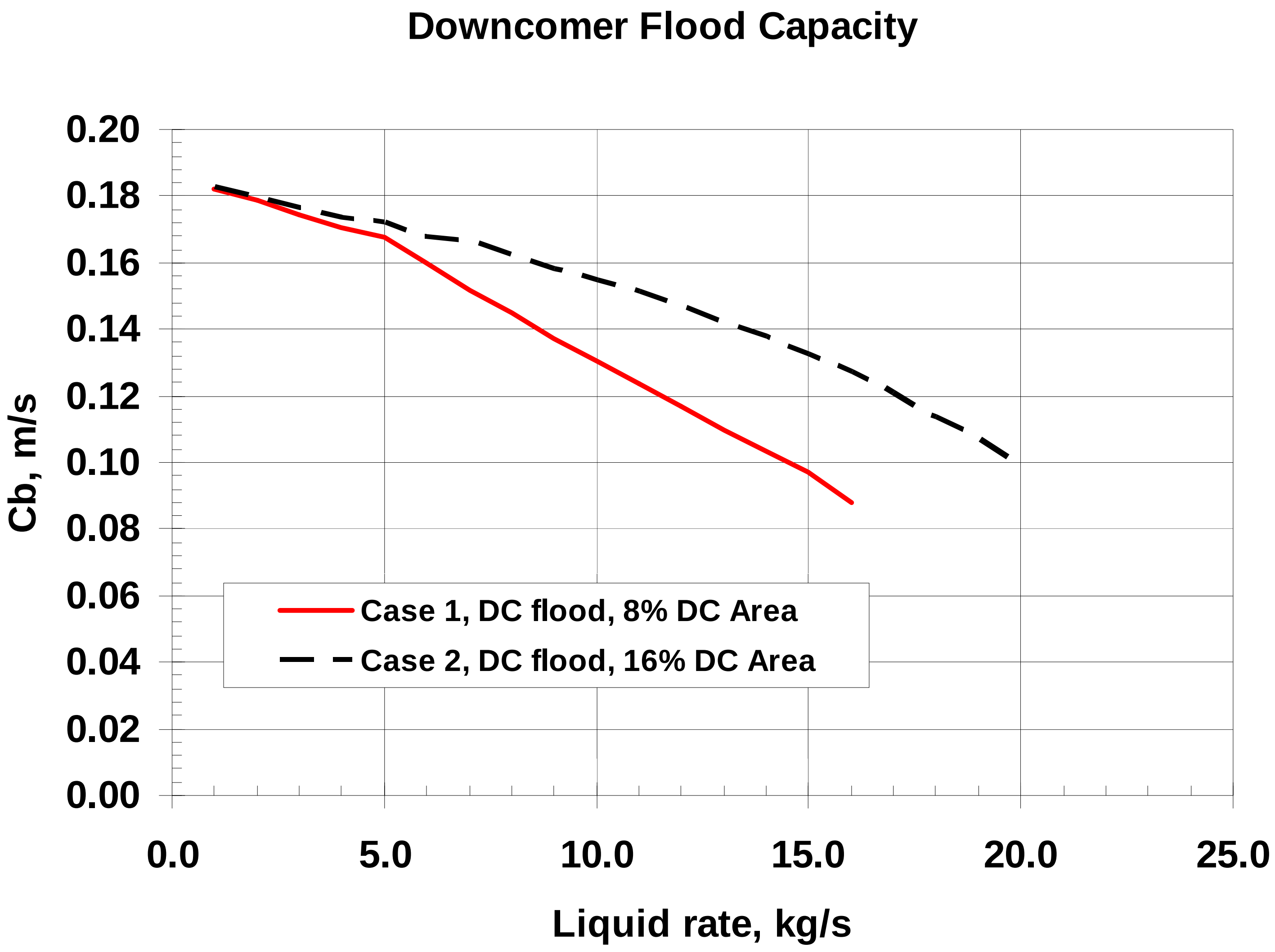
DC Choke Flooding Model Functional Analysis:

- Mainly a function of physical properties
- Depend on the DC top area
- Depend on the bubbling area
- Same model for all types of trays (sieve, valve, fixed valve) with downcomer
- Capacity advantage with sloped and truncated downcomer
- Not much depend on other tray design parameters such as tray spacing, hole size, open area, etc.

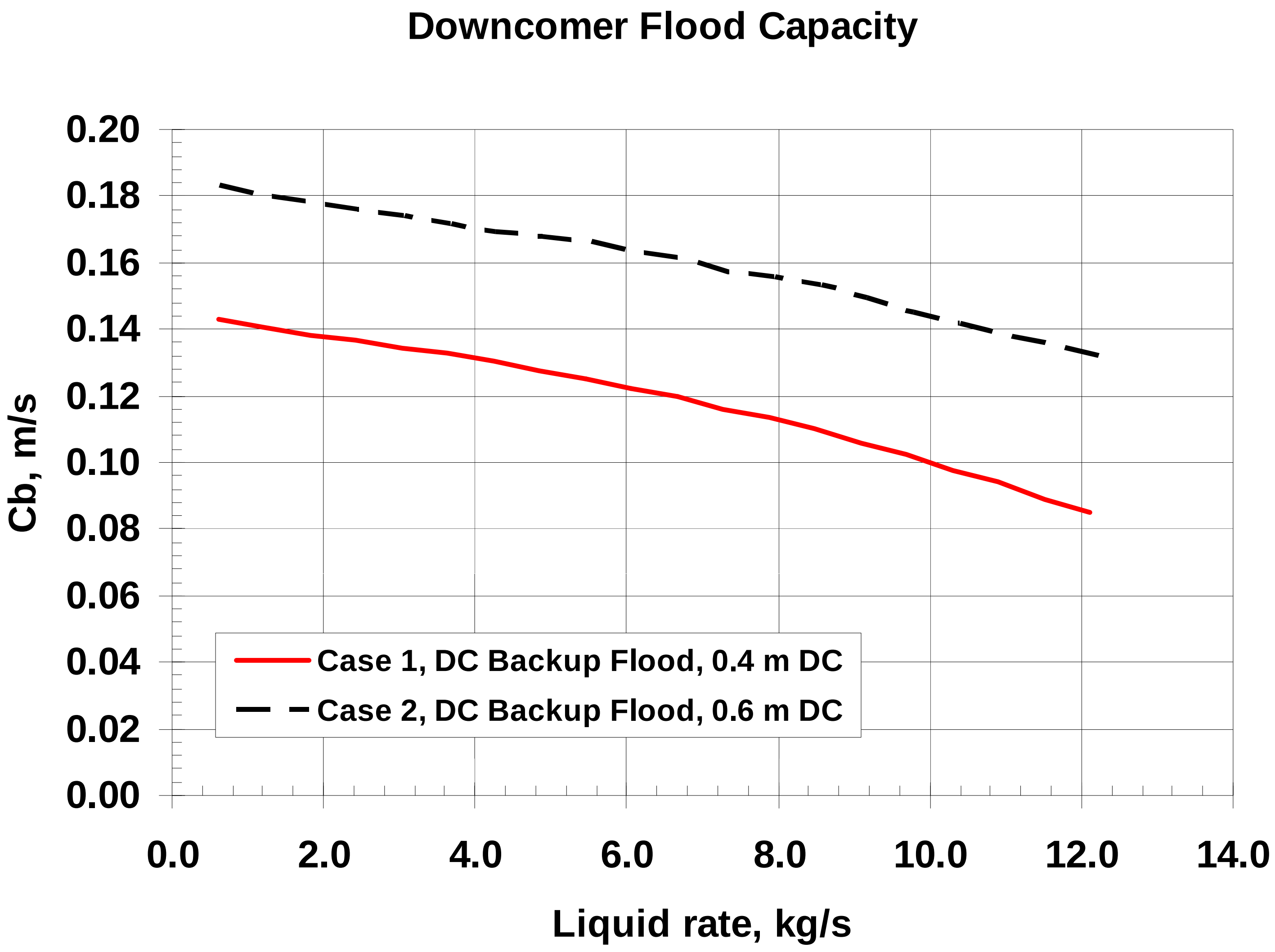
DC Backup Flooding Model Functional Analysis:

- Mainly a function of pressure drop
- Reduce pressure drop or increase tray spacing to increase DC backup flooding capacity.
- Same model for all trays with downcomer, but use different tray pressure drop and liquid holdup

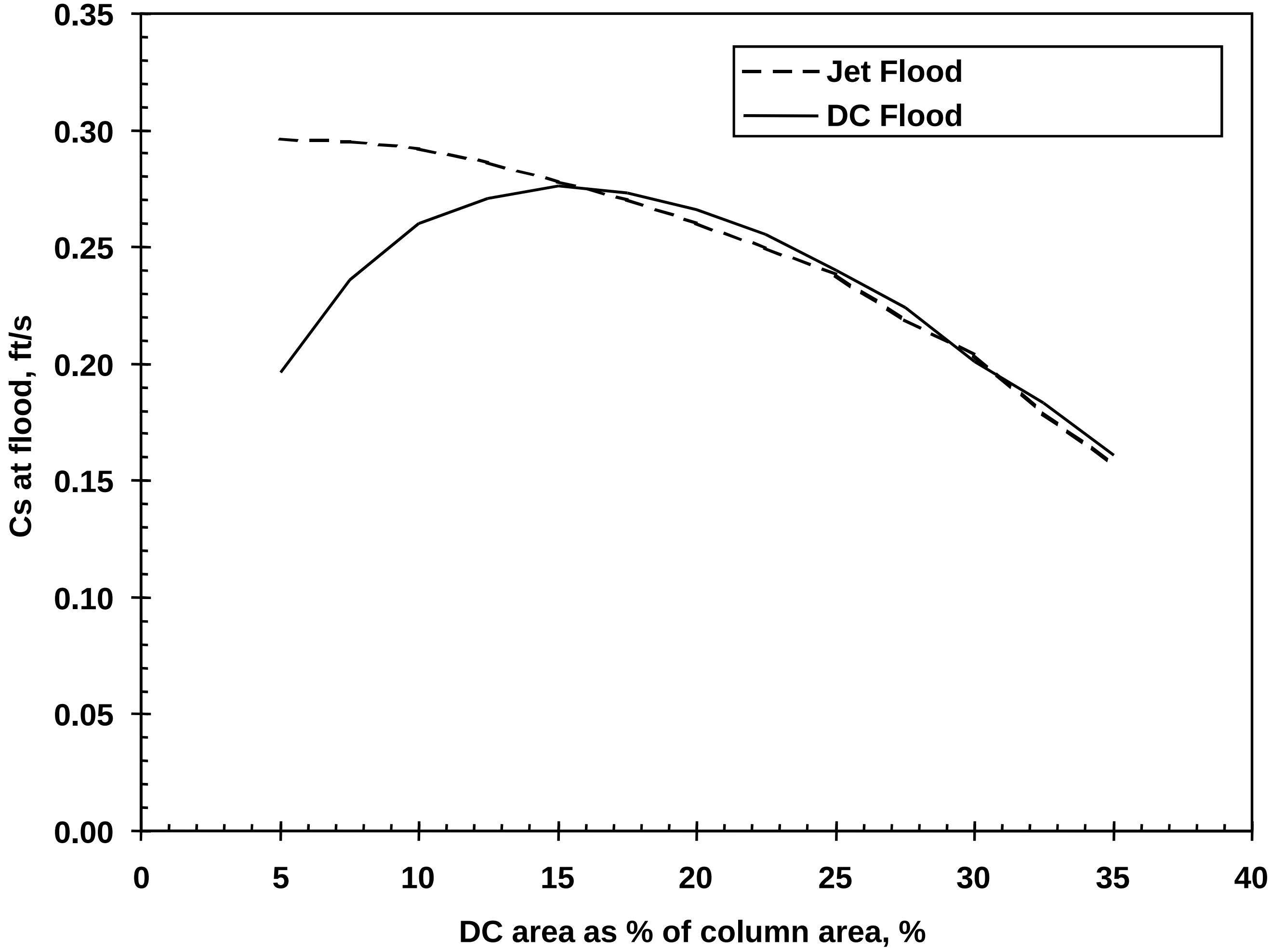
Effect of DC Area on DC Capacity



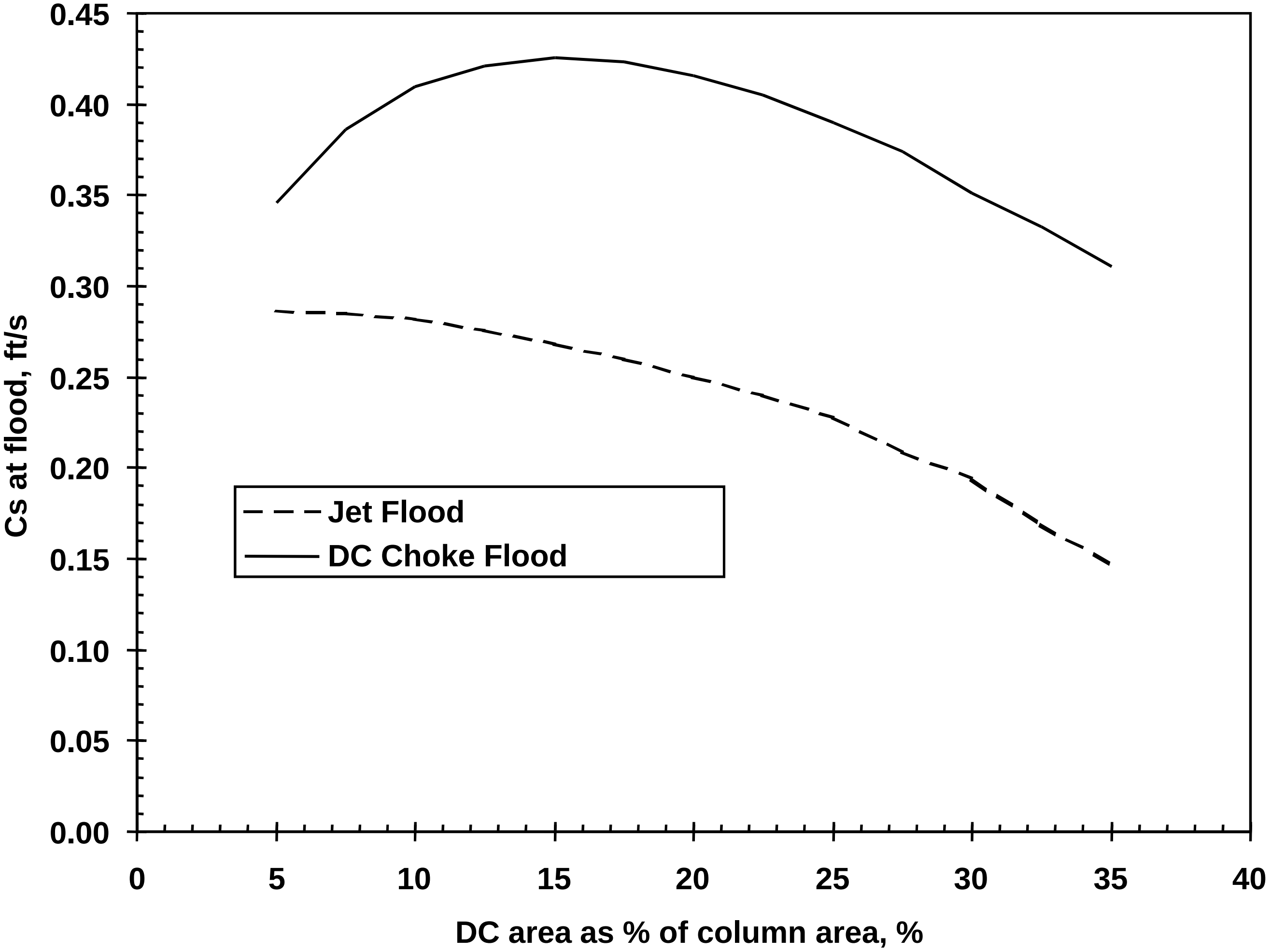
Effect of DC Depth on DC Capacity



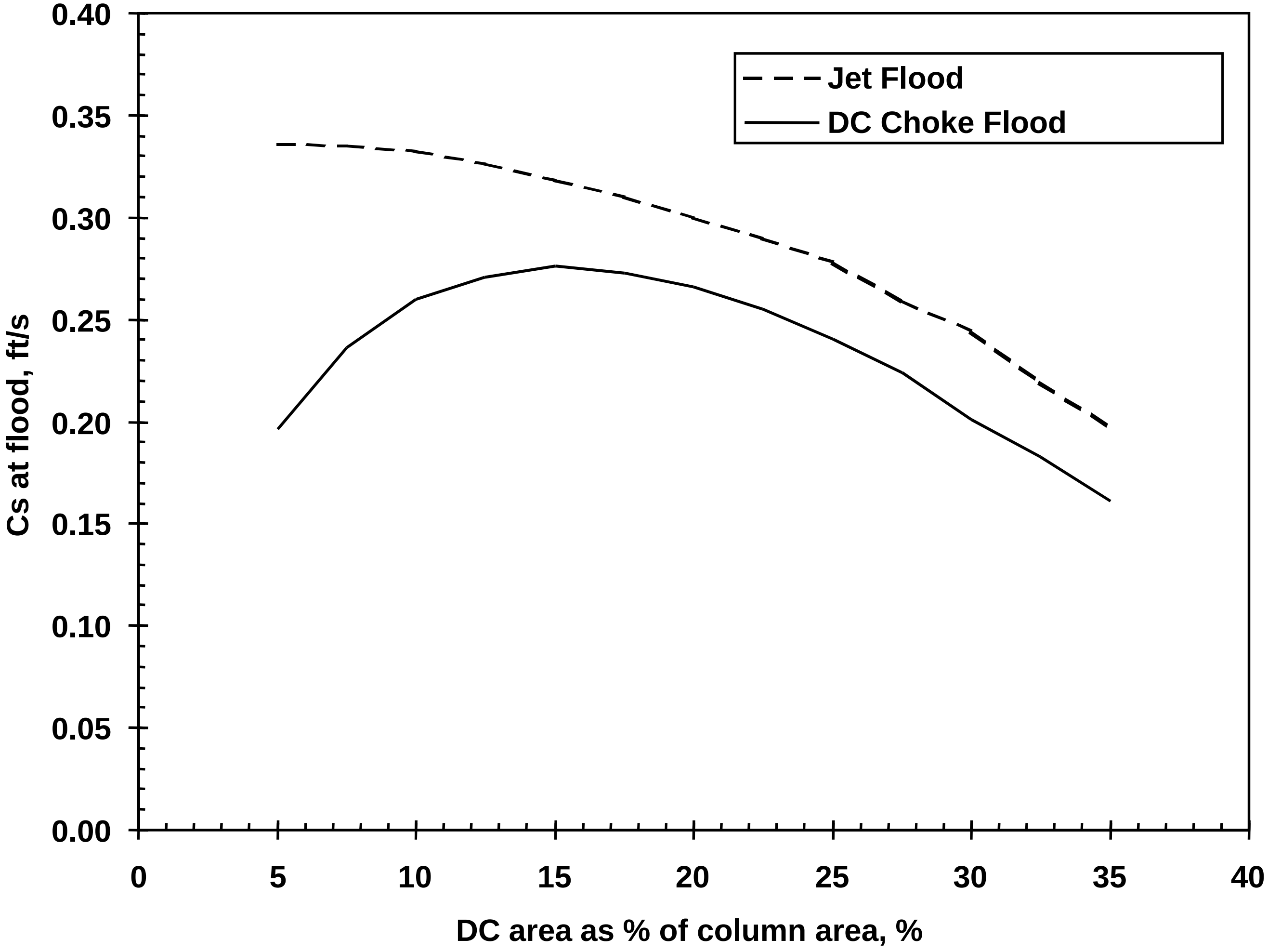
Effect of DC area on Column Capacity



Column capacity is limited by jet flood



Column capacity is limited by DC capacity



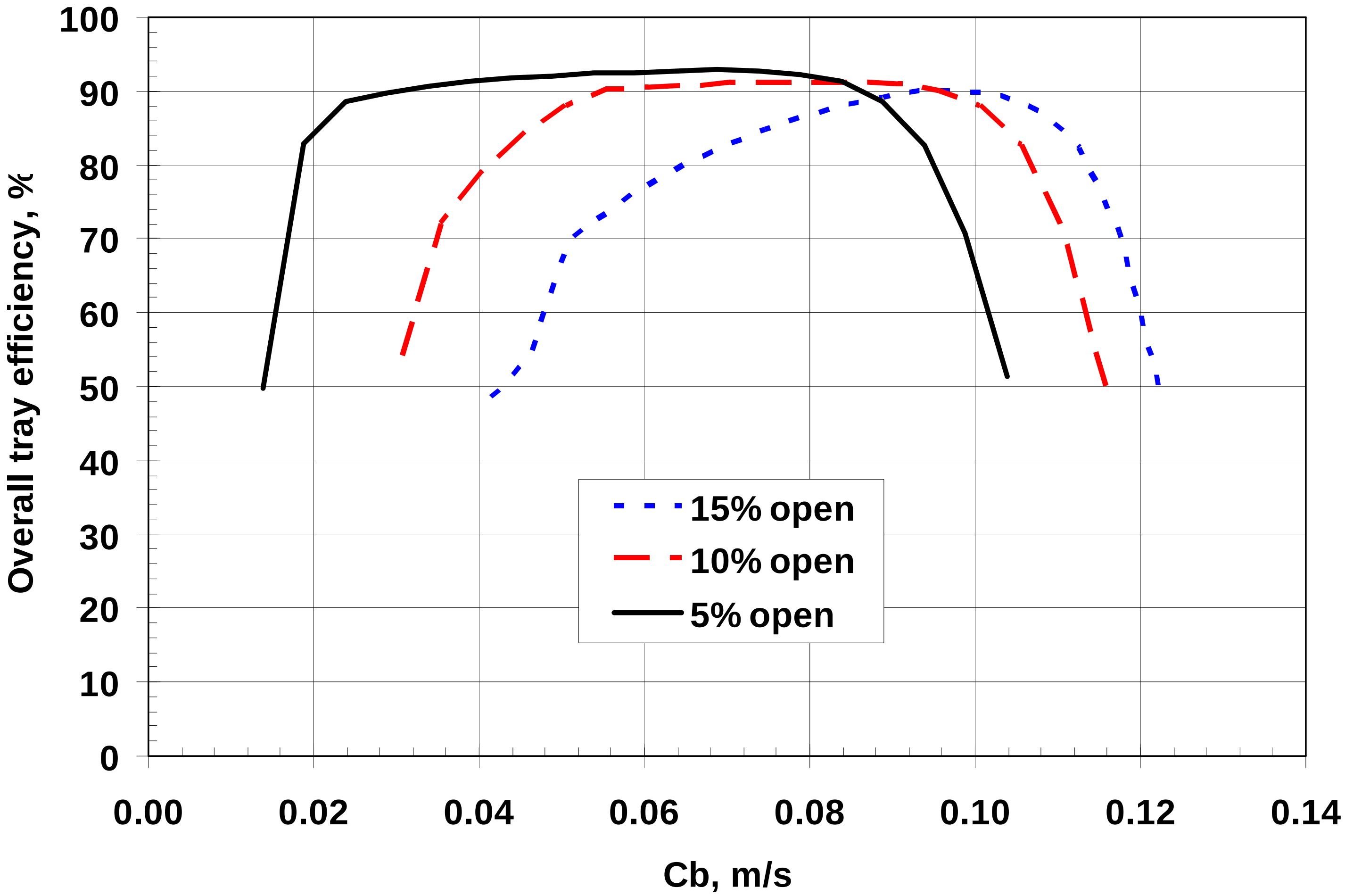
Tray Efficiency Models

1. Penetration theory
2. Two-film theory
3. Point efficiency
4. Mixing pools
5. Tray efficiency

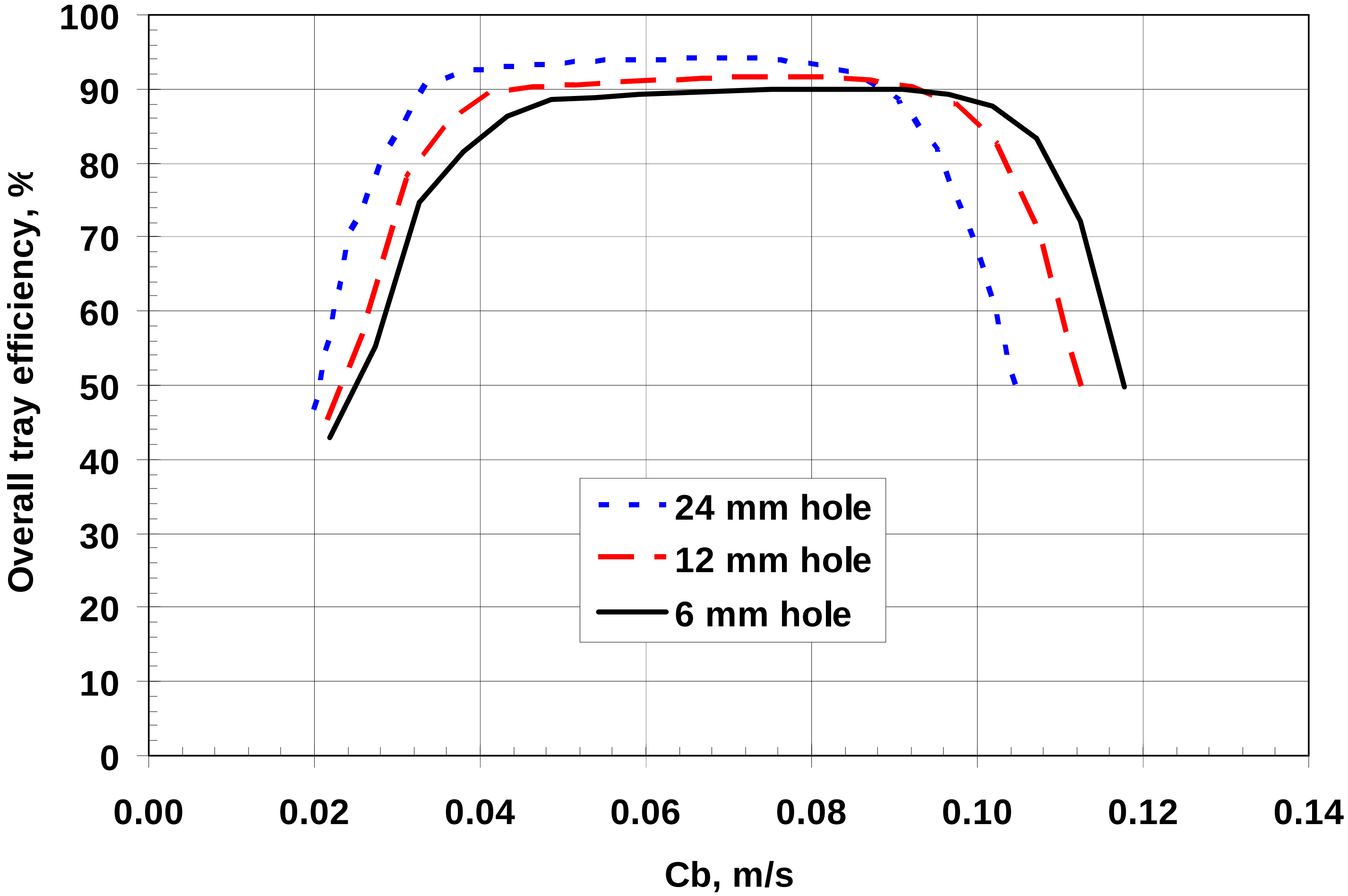
Tray Efficiency Model Functional Analysis:

- Physical properties, m, (MV/L)
- Flow path length, tray liquid mixing
- Open area
- Hole size
- Heir height

Calculated effect of open area on efficiency



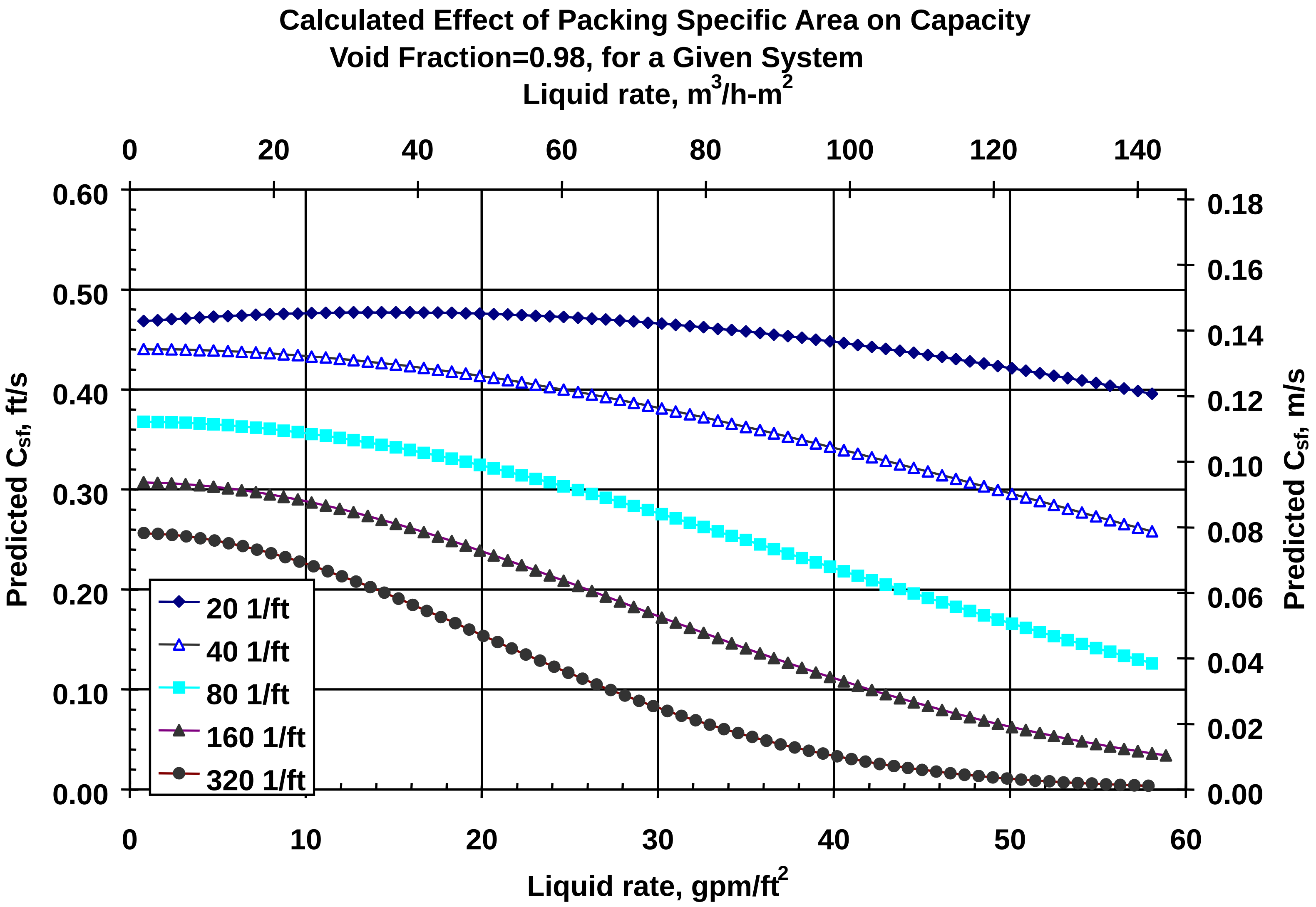
Effect of hole size on efficiency



Packing Flooding Capacity

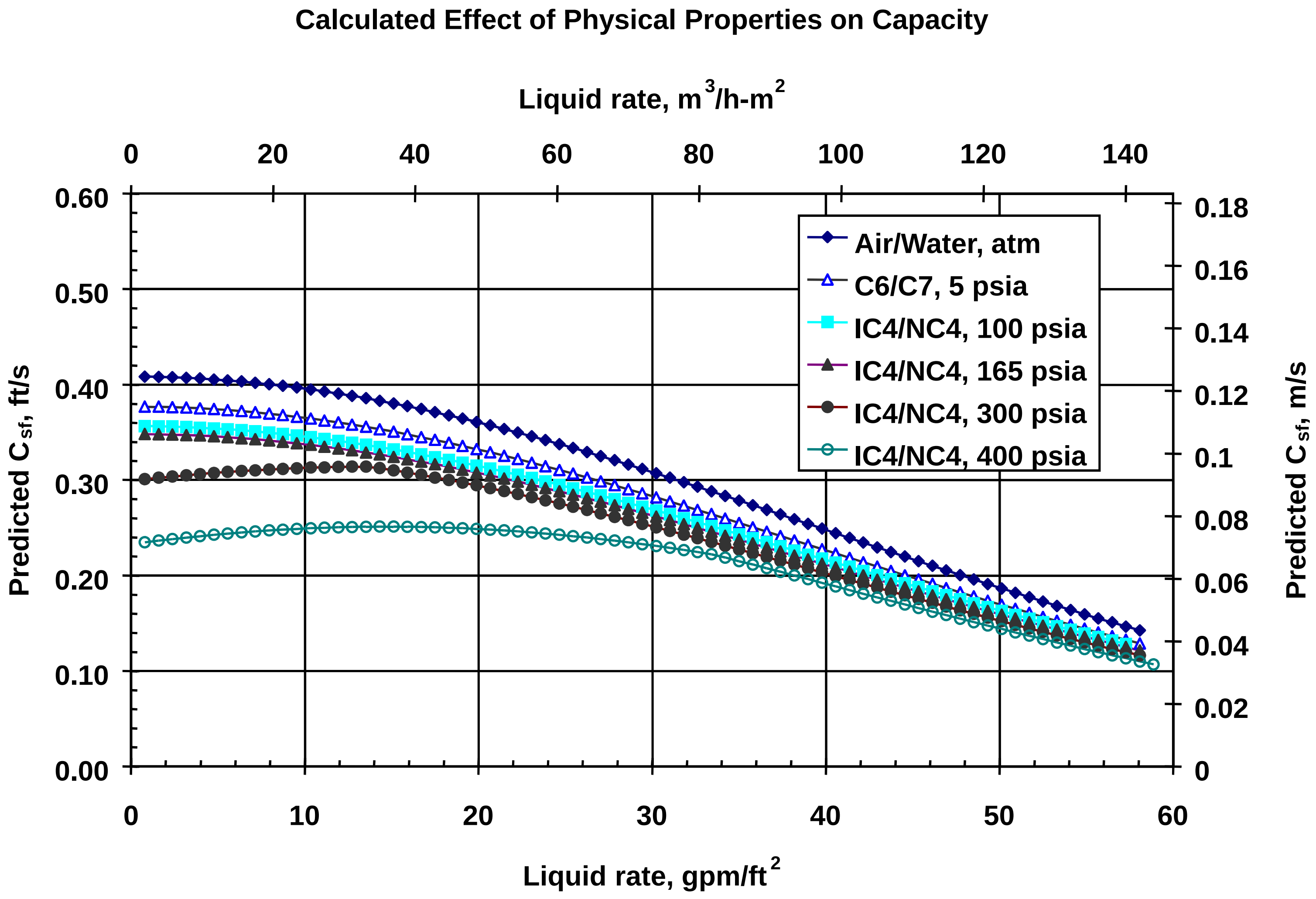
- FRI has obtained semi-empirical models for packing capacity.
- Mainly a function of packing specific area
- Crimp angle also affects capacity

Effect of packing area on packing capacity



Calculated Effect of Packing Specific Area on Capacity
Void Fraction=0.98, for a Given System

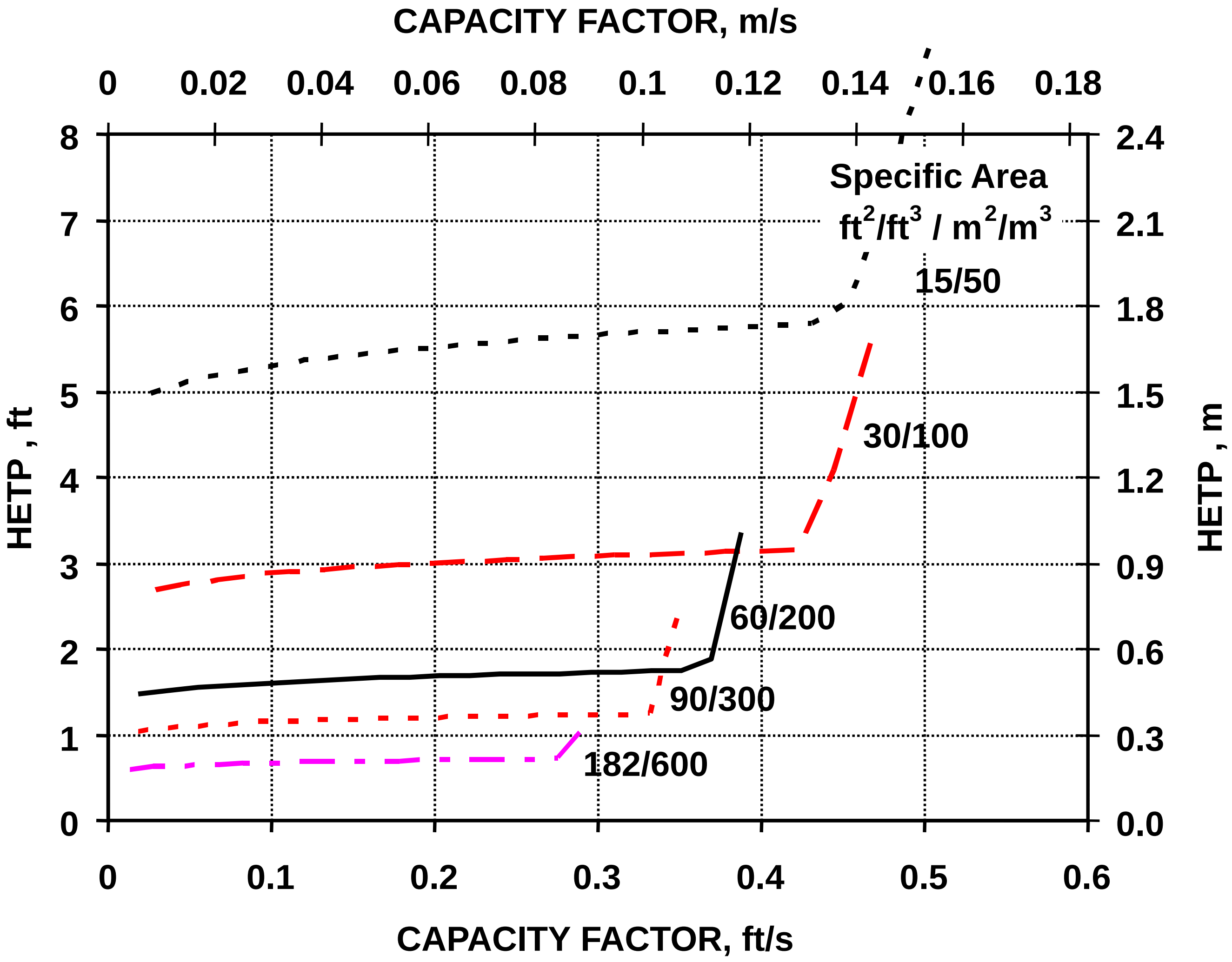
Effect of physical properties on packing capacity



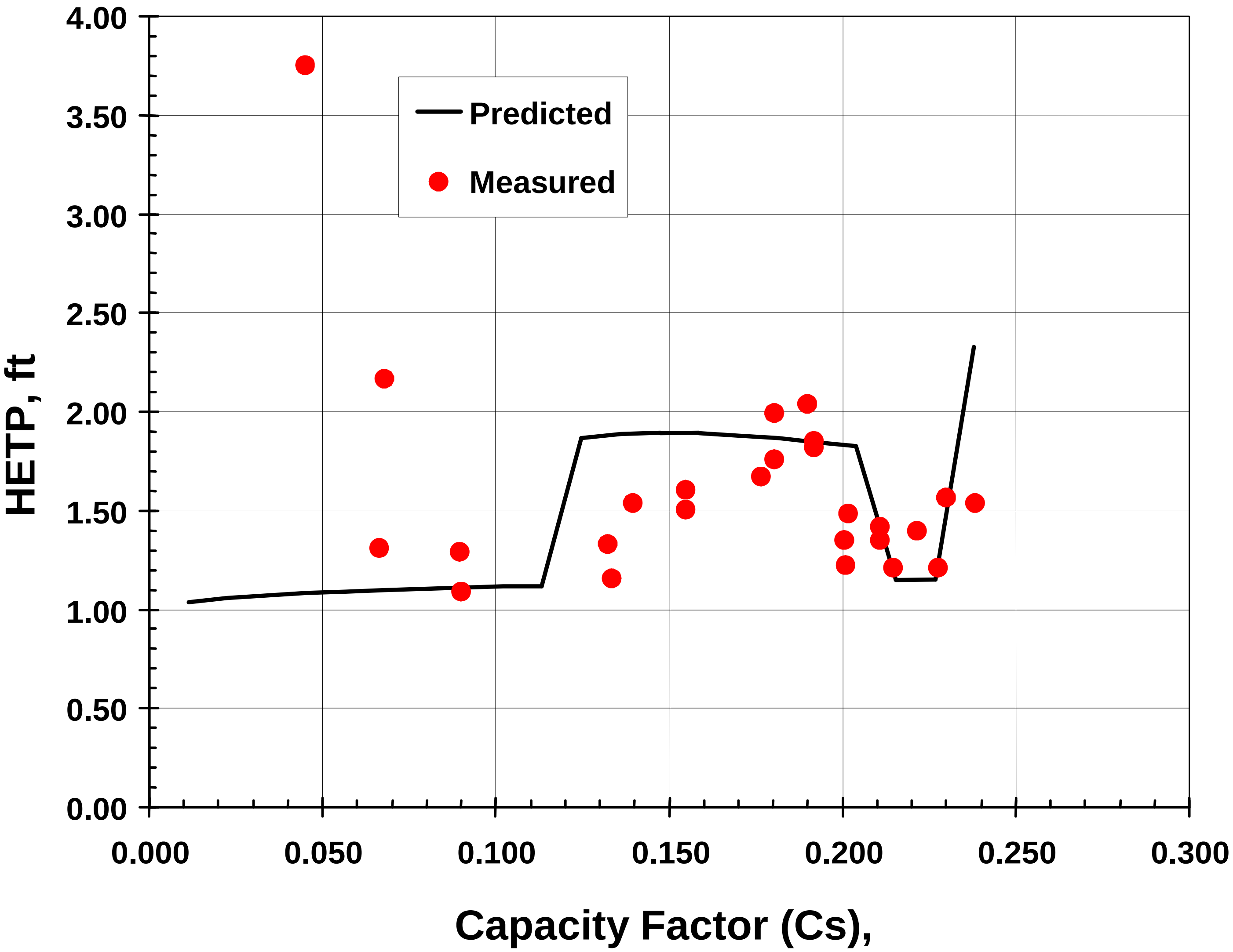
Packing Efficiency or HETP

- FRI has obtained semi-empirical models for packing HETP
- Mainly a function of packing specific area
- Crimp angle also affects efficiency
- Other factors: bed length, physical properties, m, (mV/L), hump, etc.

Effect of packing area on HETP for a low pressure system



Effect of hump on HETP for a system at 300 psia



Optimization Examples:

- Optimization results by using FRI models:
  - Vacuum: O/P Xylene, 2 psia
  - Low pressure: C6/C7, 24 psia
  - Medium pressure: IC4/NC4, 165 psia
  - High pressure: IC4/NC4, 300 psia
- Designed at 80% of flood
- Focus on capacity and efficiency only
- Tray spacing specified at 24 inches

- Capacity:
  - Minimize the column diameter (D) for a given rate
- Efficiency:
  - Minimize the HETP
- Both Capacity and Efficiency:
  - Minimize the column volume (V) for a given rate

    $V = 3.14 * HETP * D * D / 4$

O/P Xylene, 2 psia, L/V=1
Flow rates: L=V=95 klb/hr

	D, in	Eo, %	Hetp,in	Dp, in	Volume
Sieve	121	74	32	2.6/tray	6.0
Sieve, 2p	128	65	37	2.3/tray	7.84
Valve	122	76	31	3.4/tray	6.0
2” Pall	120		26	0.4/ft	4.85
M250.Y	113		15	0.38/ft	2.47

Structured packing has great advantage in terms of HETP, pressure, capacity for vacuum service.

C6/C7, 24 psia
Flow rates: V=L=370 klb/hr, 1 pass tray

	D, in	Eo, %	Hetp, in	Dp, in	Volume
Sieve	157	100	24	2.8/tray	7.67
Valve	158	98	24	3.8/tray	7.88
2” Pall	146		22	0.6/stage	6.32
M250.Y	136		13.4	0.5/stage	3.20
N4T	125		28	1.1/stage	5.67

C6/C7, 24 psia, Just Sieve Tray
Flow rates: V=L=370 klb/hr

Passes	D, in	Eo, %	Hetp, in	Dp, in	Volume
1	157	100	24	2.8/tray	7.67
2	152	97	24	3.2/tray	7.42
3	144	91	26	3.8/tray	7.09
4	152	87	28	3.7/stage	8.23

A 3-pass tray gives smallest column size and volume.

IC4/NC4, 165 psia
Flow rates: V=L=700 klb/hr, 3 pass trays

	D, in	Eo, %	Hetp, in	Dp, in	Volume
Sieve, 3p	155	111	22	4.5/tray	6.75
Valve, 3p	160	112	22	4.5/tray	7.16
2” Pall	153		19	0.4/stage	6.1
M250.Y	148		18, hump	0.6/stage	5.14
N4T	133		24		5.51

IC4/NC4, 300 psia
Flow rates: V=L=420 klb/hr

	D, in	**Eo, %**	**Hetp, in**	**Dp, in**	**Volume**
Sieve, 1p, ST	**135**	**118**	**20**	**4.0/tray**	**4.83**
Sieve, 2p, ST	**128**	**113**	**21**	**4.0/tray**	**4.51**
Sieve, 3p, ST	**121**	**105**	**23**	**6.2/tray**	**4.32**
Sieve, 4p, ST	**110**	**103**	**23**	**6.2/stage**	**3.65**
2” Pall	**120**		**20**	**0.2/stage**	**3.74**
M250.Y	**113**		**19, hump**	**0.3/stage**	**3.25**
N4T	**104**		**24, hump**	**0.35/stage**	**3.35**

Conclusions

- Optimum column designs are possible if good models are available.
- Structured packing has great advantage in vacuum service, but uncertain for high pressure system due to HUMP.
- Tray and random packing have similar capacity for high pressure system.
- Other factors not considered in this presentation also affect the choice of internals and column designs.