Advanced Coil Selection with Respect to Performance at Minimum Flow Conditions

Presented by: Gene Nelson, PE

November 12, 2018

Good Judgment

comes from experience.

Good Judgment

comes from experience.

Experience

comes from poor judgment.

LEARNING OBJECTIVES

- Why coil selections at low flow conditions are important
- Basic science regarding coil performance
- How to select coils
- How and When To Use Pumped Coils

EXPERIENCES

- When fluid flow (air or liquid) in coils and heat exchangers is too low, laminar flow conditions can result.
- Laminar flow can result in:
  - Unpredictable Heat Transfer
  - Control Valve Hunting
  - Uneven Heating and Possible Freezing Conditions
  - Higher Water Side Flow, Lower ΔT's, and Higher Pumping Costs.
  - Comfort Issues as Result of Temperature Swings

EXPERIENCES

- **Energy Conservation Measures**

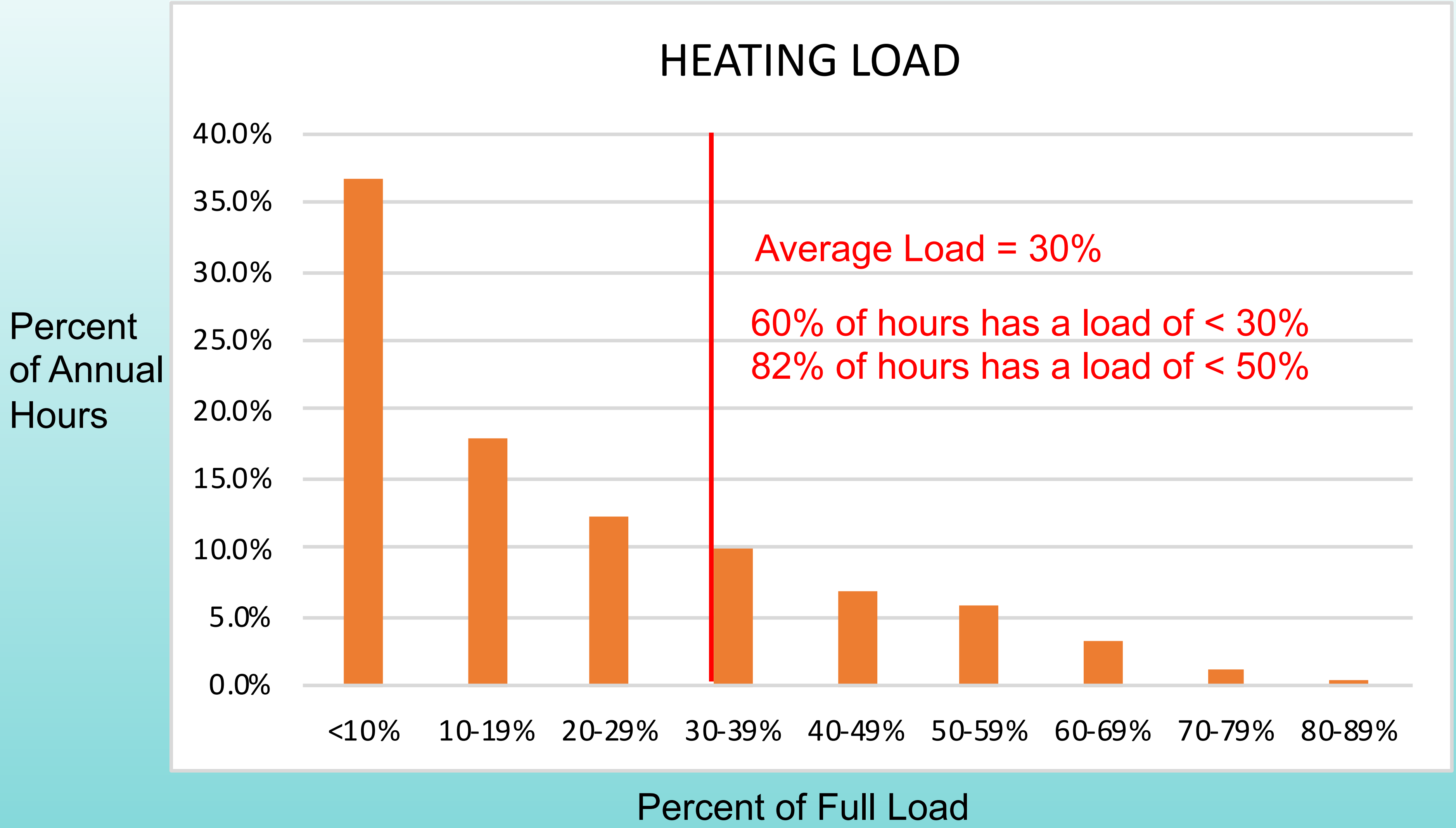
  have forced us to

  - Oversize coils to lower airside and waterside pressure drops
  - Use variable flow as much as possible

- Coils and heat exchangers operate at part load conditions over 99% of the time, up to 70% below 50%.
  - Low loads usually occur in spring and fall and during unoccupied times

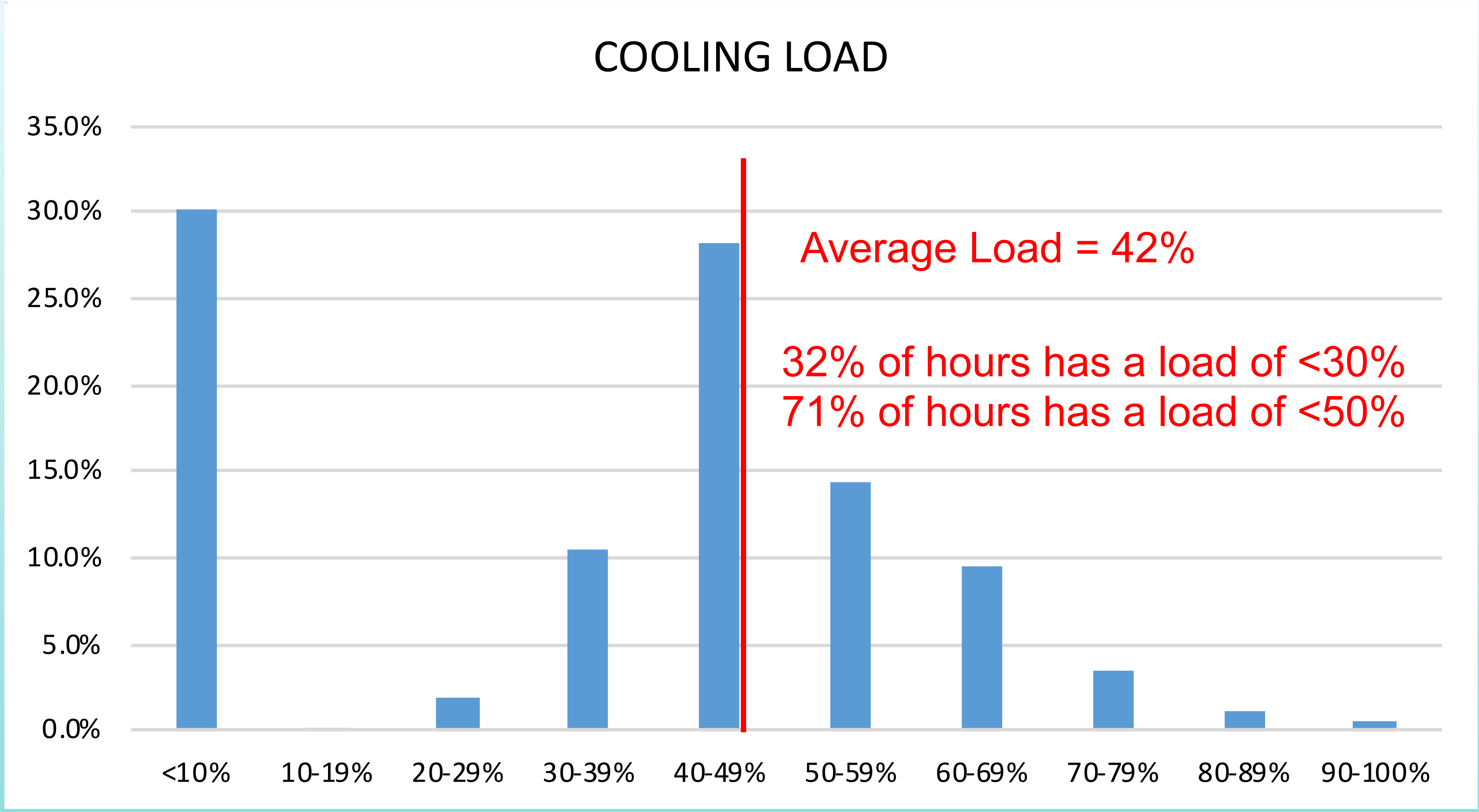
HEATING PART LOAD HOURS

FOR A SAMPLE 600,000 SF LABORATORY



COOLING PART LOAD HOURS

FOR A 600,000 SF LABORATORY



Percent of Annual Hours

Percent of Full Load

OTHER CONSIDERATIONS

- Central equipment should be capable of operating down to minimum load conditions
  - Consider multiple boilers and chillers for turndown
- Minimum turndown may not be important for Booster/reheat coils and other terminal devices

  if you accept their on/off mode of operation!

- Coil Selection is Important
- **Basic Science**
- Coil Selection
- Pumped Coils

$$q = h_c A_s (t_s - t_h)$$

Equation 2 from 2017 ASHRAE Handbook of Fundamentals, Chapter 4

where:

q = energy transfer (BTU/Hour)

h_c = convective heat transfer coefficient (BTU/Hr-SF-F)

A_s = heat transfer area (SF)

t_s = surface temperature (^oF)

t_h = fluid temperature (^oF)

$Nu = hL_c/k = f(Re_{Lc}Pr)$

Where: Nu = Nusselt number

- h = convective heat transfer coefficient
- Lc = characteristic length
- Re_{Lc} = Reynolds number = $\rho V_{Lc}/u$ = V_{Lc}/v
- V = fluid velocity
- Pr = Prandtl number = $c_p u/k$
- c_p = fluid specific heat
- u = fluid dynamic viscosity
- ρ = fluid density
- v = kinematic viscosity = u/ ρ
- k = fluid conductivity

FLUID FLOW IN TUBES

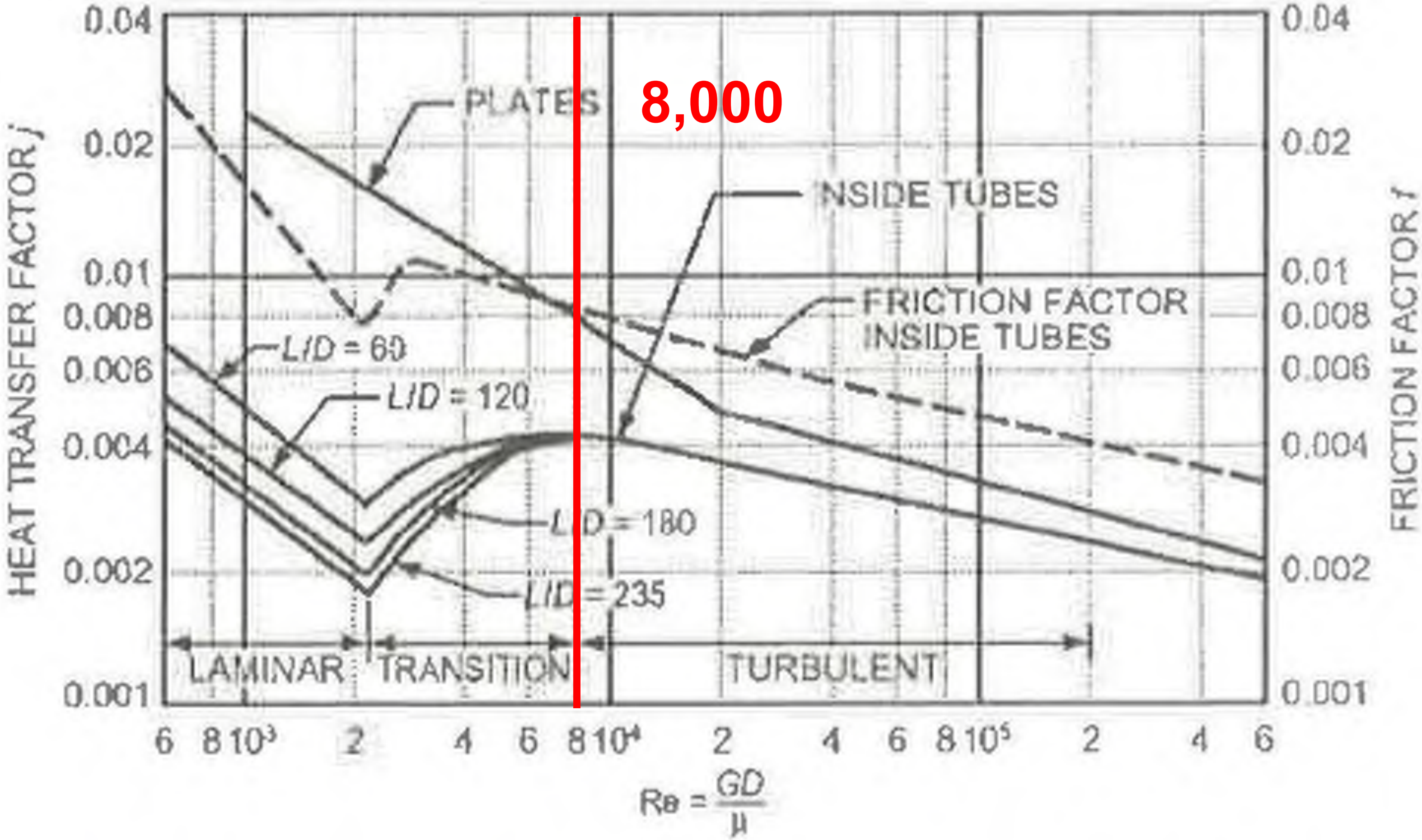


Fig. 20 Typical Dimensionless Representation of Forced-Convection Heat Transfer

Figure from 2017 ASHRAE Handbook of Fundamentals, Chapter 4

FLUID FLOW IN TUBES

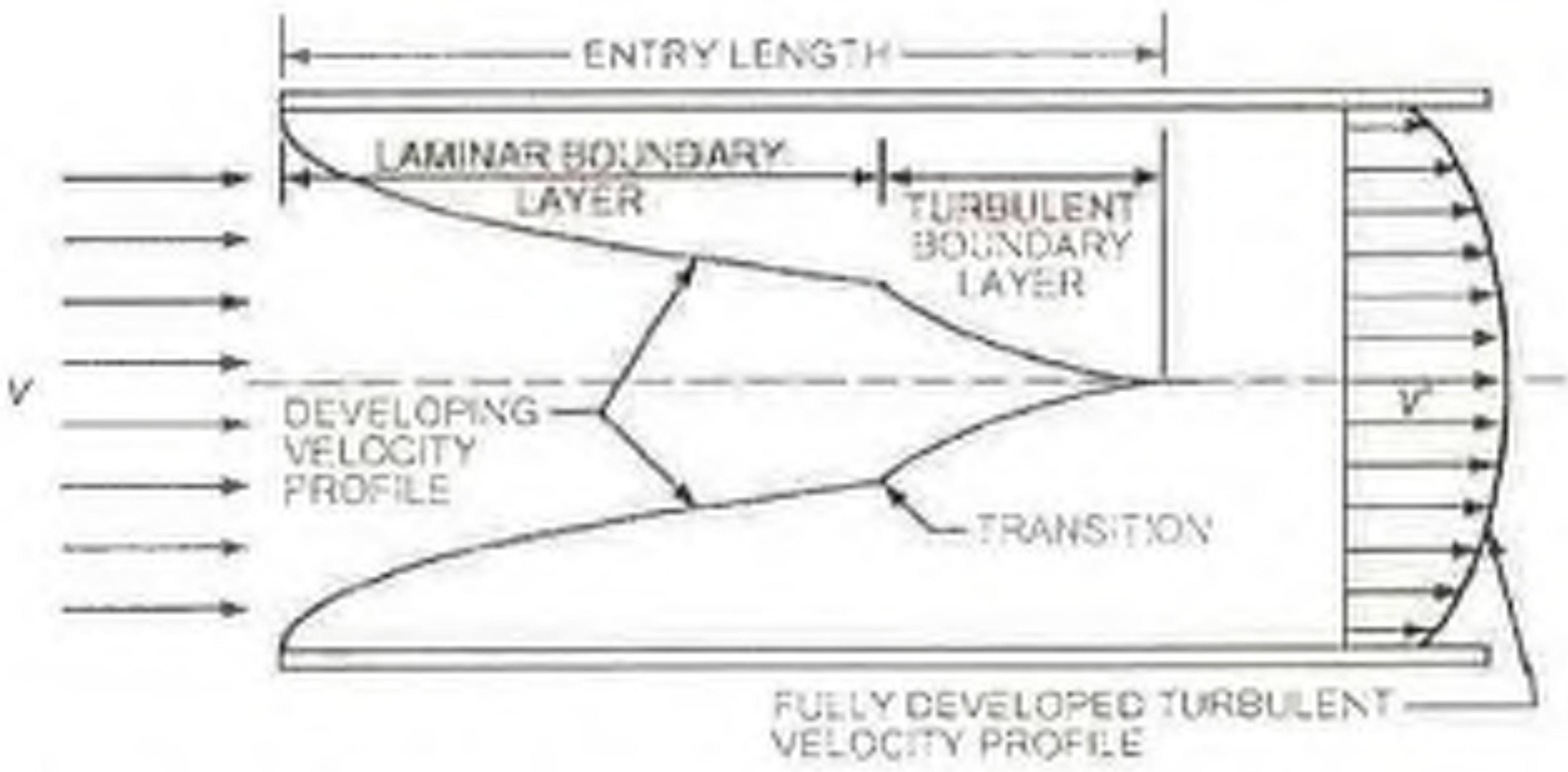


Fig. 19 Boundary Layer Build-up in Entrance Region of Tube or Channel

Figure from 2017 ASHRAE Handbook of Fundamentals, Chapter 4

KINEMATIC VISCOSITIES VS TEMPERATURE

Table 1
Kinematic Viscosity of Fluids (x 10^{-5} ft^2/sec)

Water Temp. (°F)	Water	30% by vol. of EG	40% by vol. EG	30% by vol. PG	40% by vol. PG
40°F	1.72	4.324	7.078	5.228	8.268
100°F	0.758	1.568	1.958	1.91	2.318
180°F	0.421	0.643	0.796	0.719	0.870

MINIMUM TUBE VELOCITIES FOR TURBULENT FLOW

Table 2 Minimum Tube Velocity (fps) For Turbulent Flow			
Fluid/ Temperature (°F)	**40°F**	**100°F**	**180°F**
Water	1.44	0.63	0.35
30% EG	3.61	1.31	0.54
40% EG	5.91	1.63	0.66
30% PG	4.36	1.59	0.60
40% PG	6.90	1.94	0.73

AIRSIDE MINIMUM VELOCITIES

$$Nu = hL_c/k = f(Re_{Lc}Pr)$$

Where: Nu = Nusselt number

h = convective heat transfer coefficient

(BTU/Hr-SF-F)

Lc = characteristic length

Re_{Lc} = Reynolds number = $\rho V_{Lc}/u = V_{Lc}/v$

V_{Lc} = Flat plate velocity

v = kinematic viscosity = u/ρ

u = fluid dynamic viscosity

ρ = fluid density

AIRSIDE MINIMUM VELOCITIES

Turbulent flow starts with Re between 300,000 and 500,000
The more irregular the fin shape, the lower the number
Also a function of fin spacing

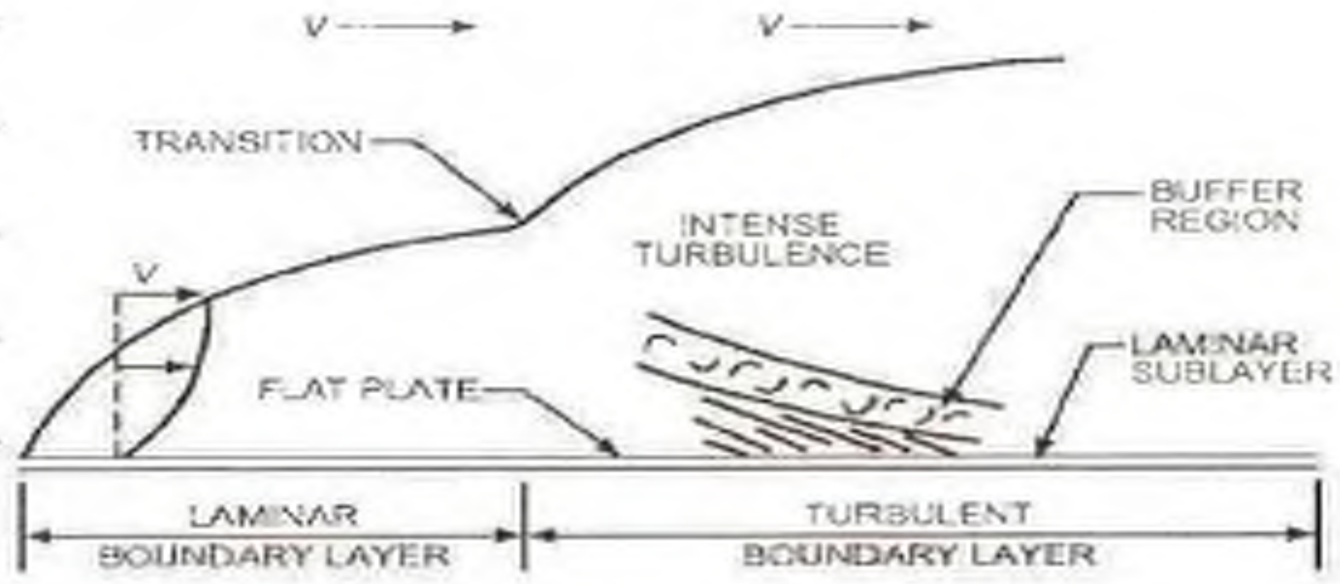


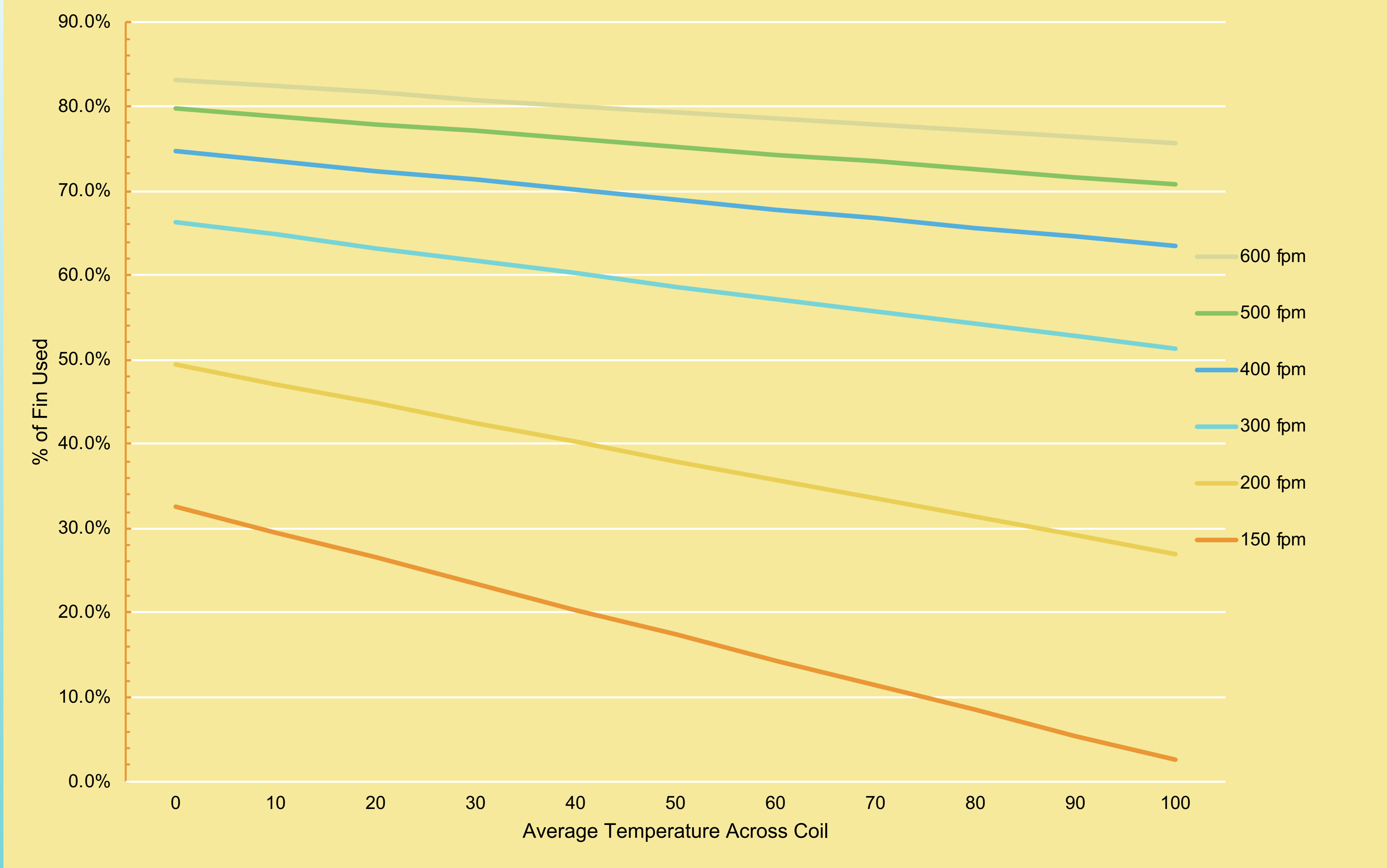
Fig. 18 External Flow Boundary Layer Build-up
(Vertical Scale Magnified)

Figure from 2017 ASHRAE Handbook of Fundamentals, Chapter 4

Table 3 Kinematic Viscosity of Air (v) ft^2/sec at various temperatures
cold air (0°F at 80% RH) $v = 1.264 \times 10^{-4}$
medium air (60°F @ 80%RH) $v = 1.607 \times 10^{-4}$
warm air (100°F@ 40% RH) $v = 1.826 \times 10^{-4}$

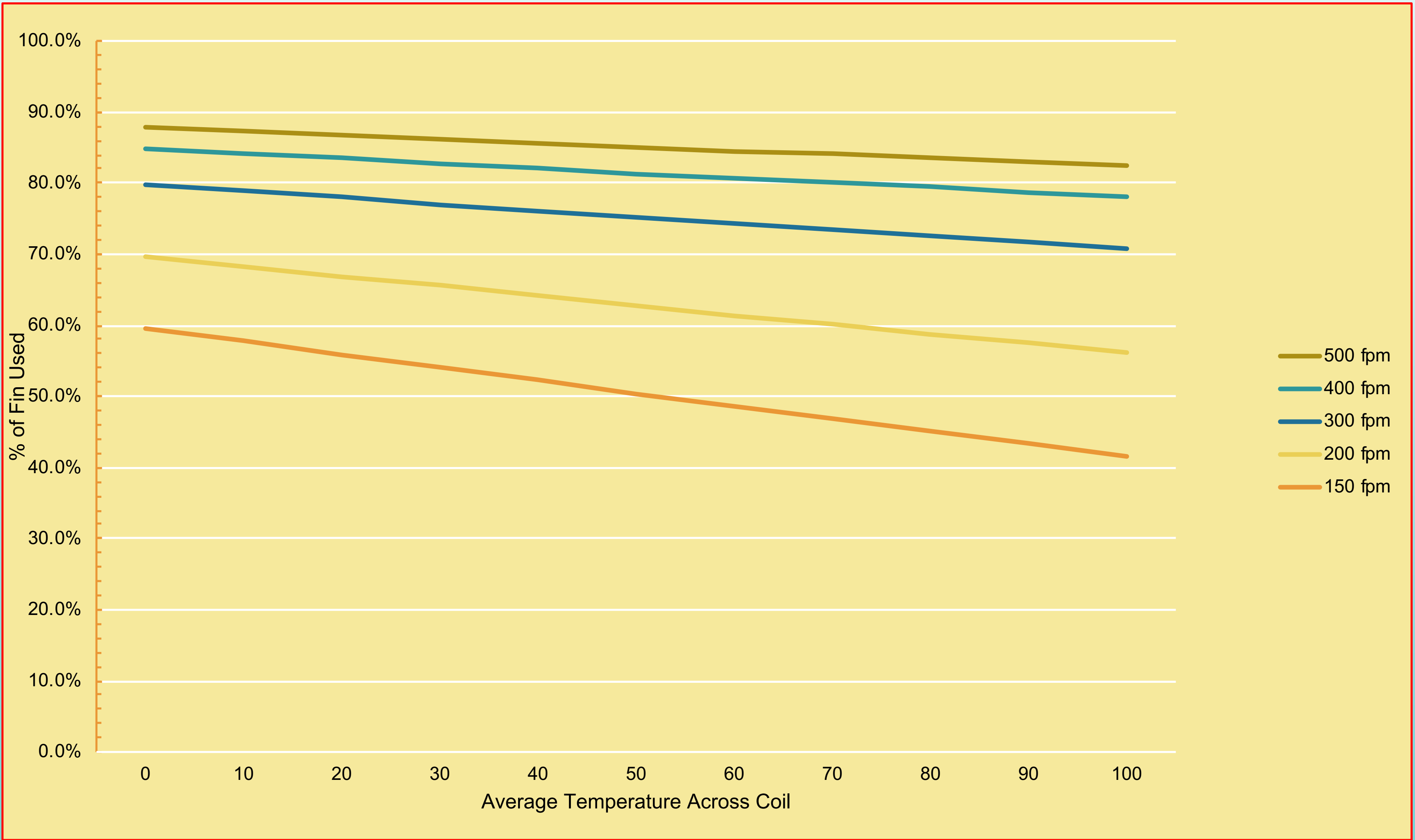
Effective Coil Area

Function of Face Velocity for
1 Row Booster Coil (4.5” depth)



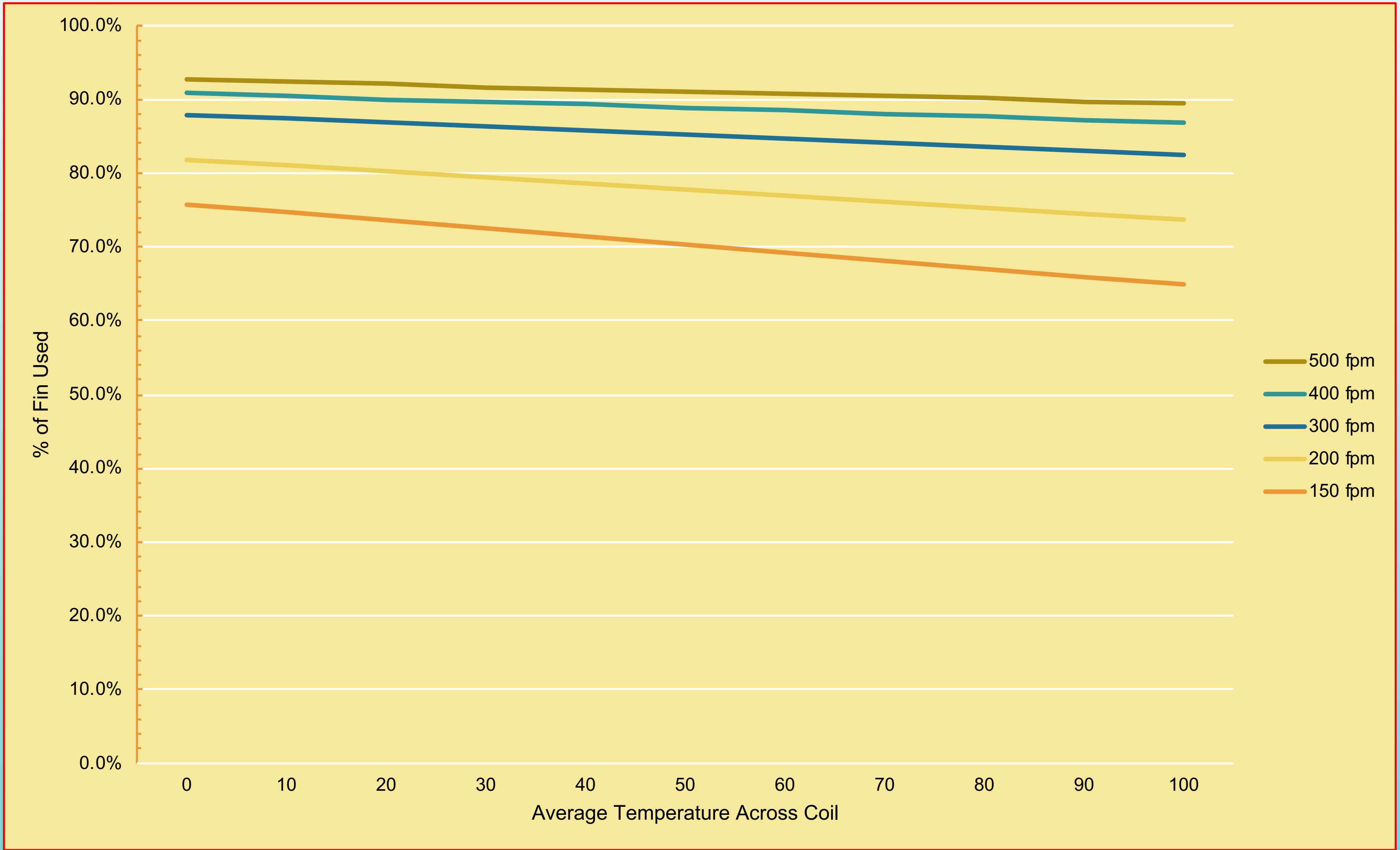
Effective Coil Area

Function of Face Velocity for
4 Row Coil (7.5” depth)



Effective Coil Area

Function of Face Velocity for 8 Row Coil (12.5" depth)



CONCLUSIONS

- Coil depth is a factor
- 1 row coils should only be used for small booster coils and should not be used for cooling or preheat coils, especially for VAV systems

- Coil Selection is Important
- Basic Science
- Coil Selection
- Pumped Coils

RECOMMENDED MINUMUM COIL FACE VELOCITIES (FPM)

COIL DEPTH	1 ROW	2 OR 3 ROWS	4 ROWS	6 ROWS	8 ROWS
COOLING	N/R	300	300	250	200
PREHEAT	N/R	400	300	250	200
REHEAT	300	200	200	200	200

What have we learned so far?

- Coil Selection is Important
- Basic Science
- **Coil Selection**
- Pumped Coils

- Minimum tube velocities are important
  - Function of fluid type and temperature
  - Flow will become laminar at some point as flows decrease.
  - Based on load profiles, attempt to pick coils with turbulent flow for most of the hours at part load conditions. (Down to as far as possible)
  - With 6 fps, turndown is only 4:1 for cooling, up to 10:1 for heating

- Minimum face velocities are important
  - Function of air temperature and coil depth

RECOMMENDED MINIMUM TUBE VELOCITIES

RECOMMENDED MINIMUM TUBE VELOCITIES (FPS)			
	COOLING 40-45^{O}F	LOW TEMP HEATING 90-140^{O}F	STD TEMP HEATING 160-200^{O}F
WATER	1.5 - 2	1.0 - 1.5	0.4 - 0.6
30% EG/PG	4 - 5	1.5 - 2	0.6 - 1
40% EG/PG	AVOID	2 - 3	0.8 - 1.5

2016 ASHRAE Systems Handbook – Ch. 23 and 27 discuss coil selection.
Max. tube velocity = 6 fps for copper

ASME Std AG-1: 2 fps min.

AHRI Std 410: 1 fps min., Re min = 3700

RECOMMENDED MINIMUM COIL VELOCITIES (fpm)

COIL DEPTH	1 ROW	2 OR 3 ROWS	4 ROWS	6 ROWS	8 ROWS
COOLING	N/R	300	300	250	200
PREHEAT	N/R	400	300	250	200
REHEAT	300	200	200	200	200

Coil Selection

(GIVEN: max. airflow, EAT/LAT conditions)

- **<u>Step 1 of 7</u>: Determine airside and water side turndown rates.**
  - Sum minimum VAV box settings
  - Account for damper closures (fire/smoke, unoccupied zone dampers, etc.)
  - Operating both AHUs when parallel units are used for 100% or partial redundancy
  - Water side turndown should be as much as possible given 6 fps max.

Coil Selection

- **<u>Step 2</u>: Determine number of coils and coil sizes using maximum and minimum face velocities**
  - Maximum face velocity for cooling coils should be less than published coil carryover values (<550 fpm)
  - No maximum face velocity for heating coils.
    - Practical limit is 900 fpm for AHU coils and 1500 for reheat coils
  - Determine minimum face velocity based on system turndown.
  - Determine if multiple coils/AHUS are required or if shutoff or face and bypass dampers are required to keep face velocity above minimum values.

Coil Selection

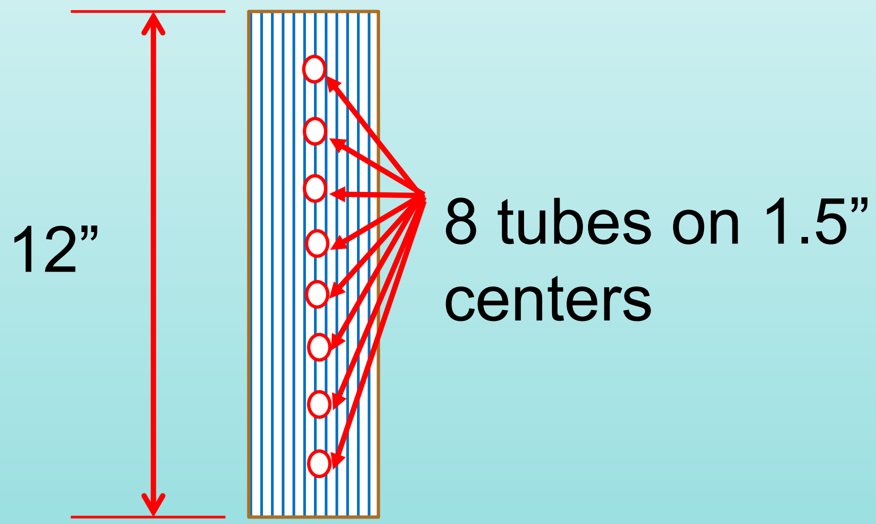
- **<u>Step 3 (Optional)</u>: For <u>custom AHU coils</u>, consider**
  - Selecting number off tubes in coil face to achieve proper circuiting
  - Limiting the size of coils to improve drain pan collection efficiency, ease of maintenance and ease of coil replacement.
  - For ease of coil replacement, consider limiting the coil length to about 120”.
  - Consider multiple, staggered coils if length exceeds 120”.

Coil Selection

- **Step 3a: Select coil height based on number of tubes, tube size, and circuiting to achieve desired tube velocity**
  - Number of tubes in coil face is a function of coil height
  - Tube sizes (3/8”, 1/2”, 5/8”)
  - Circuiting Options
    - Full or 1 – All tubes in face have equal full.
    - Fraction circuiting (0.25, 0.33, 0.5, 0.75) – Multiple tubes are circuited together to increase tube velocity
    - 1.5, 2 (double), and 3 (triple) circuiting – Flow is divided to coil to reduce tube velocity

Coil Selection

- Number of coil tubes = coil height (in.) / 1.5” per tube



- Total no. of tubes = tubes/coil ht. x no. of rows

Coil Selection

- Tube velocities vs tube sizes

TUBE VELOCITY PER TUBE FOR 1 GPM			
Tube Size (OD in.)	Tube ID (in)	Tube Area (sf)	FPS / 1 GPM
3/8	0.035	0.000506944	4.395
1/2	0.402	0.000881944	2.526
5/8	0.527	0.001513889	1.472

1 gpm = 0.00222801 ft^3/sec.

Coil Selection

- **Step 3b: Based on coil height and desired face area, determine**
- Coil length (in) =
  Coil area sf x 144 / coil height (in)

Coil Selection

- **<u>Step 4</u>: Based on coil height and initial guess at circuiting, determine**
- Select tube size (diameter)
- No. of circuits =

  No. of tubes in coil height x circuiting number (percentage)
- Flow per circuit =

  Total coil flow / no. of circuits
- Estimated tube velocity =

  gpm/circuit x fps/gpm
- Repeat above steps to get desired tube velocity (6 fps max.)

Coil Selection

- **<u>Step 5</u>: Start using coil selection software. Select tube and fin materials, and if any coatings are to be used.**
  - Notes
    - Booster coil software will preselect materials for you and limit coil sizes.
    - Certain material options may be fixed by coil manufacturer

Coil Selection

- **Step 5a:** **Enter air flow, EAT, and EWT conditions**
  - Consider using adjusted EWTs when using pumped coils
- **Step 5b:** **Enter either LAT conditions, total MBH, or water flow, but not more than one**
  - Best option is to enter water flow based on desired temperature change
  - Consider using higher water flows when using pumped coils to maintain minimum tube velocities

Coil Selection

- **<u>Step 5c:</u> Enter first guess of coil selection**
  - Coil type
  - Coil size
  - No. of rows (1 through 12)
  - Circuiting (quarter, third, half, three-quarter, full, 1.5, double, triple)
  - Tube diameter (3/8”, 1/2”, 5/8”)
  - Tube wall thickness (0.016” to 0.049”)

Coil Selection

- **<u>Step 5c:</u> Enter first guess of coil selection**
  - Fin Thickness (0.006” to 0.01”)
  - Fin material (aluminum, copper, SS)
  - Fin shape (flat, wave, enhanced wave)
  - Fin coatings for corrosion resistance (baked phenolic, sprayed epoxy)
  - Casing material (Galvanized or SS)
  - Header connection sizes
  - LH or RH end connections

Coil Selection

- **Step 6: Adjust water flow or circuiting to maintain minimum tube velocities**
  - Adjust circuiting first
  - Fine tune by minor flow adjustments
  - More options with pumped coils
    - Pumped coil flows will may be higher than system flows

Coil Selection

- **<u>Step 7:</u> Adjust above inputs to achieve desired LAT/MBH**
  - Consider fin spacing/type as first adjustment
  - Adjust water temps for pumped coils
  - Consider no. of rows if capacity needs a major adjustment

Coil Selection Summary

- Determine minimum flow conditions
- Use iterative process to achieve maximum desired capacity while maintaining turbulent flow at minimum flow conditions

Coil Selection Summary

- Look at ways to reduce heat exchange areas at low loads
  - Multiple heat exchangers, AHUs, etc.
  - Some coils (Especially 8 row cooling coils) can have multiple headers to split the coil vertically. Each header with separate control valves can be sized for 50% flow thus improving the turndown.

  - 1/3 + 2/3 or 2 @ 50% heat exchangers with separate control valves

Coil Selection Example

- Coil Selection is Important
- Basic Science
- **Coil Selection**
- Pumped Coils

Given:

Air flow: 10,000 cfm
EAT: 80^{o}F DB/67^{o}F WB
Desired output: 52^{o}F DB / 51.8^{o}F WB (462.8 MBH)
EWT: 42^{o}F
Ideal water ΔT: 14-16^{o}F

Step 1:

Air Turndown: 40% or 4,000 cfm
Ideal 100% Flow: 57.9 - 66.1 gpm based on ΔT

Step 2:

Coil size: 1 coil at 20 sf, 500 fpm @ 100% flow
200 fpm @ 40% flow)

Coil Selection Example

<u>Step 4:</u>

Determine circuiting

- Based 36” high coil, no. of tubes in face = 36” / 1.5” = 24 tubes
- With 5/8” tubes, 1 gpm = 1.472 fps
- With full circuiting, tube velocity = 1.472 fps x 66 gpm/24 tubes = 4.0 fps
- Tube velocity @ 25% flow = 1.0 fps (A bit too low)
- Try half circuiting, tube velocity = 1.472 fps x 66 gpm /24 x 0.5 tubes = 8.1 fps
- Tube velocity @ 25% flow = 2.0 fps
- Try half circuiting

Coil Selection Example

Step 5:

Enter data:

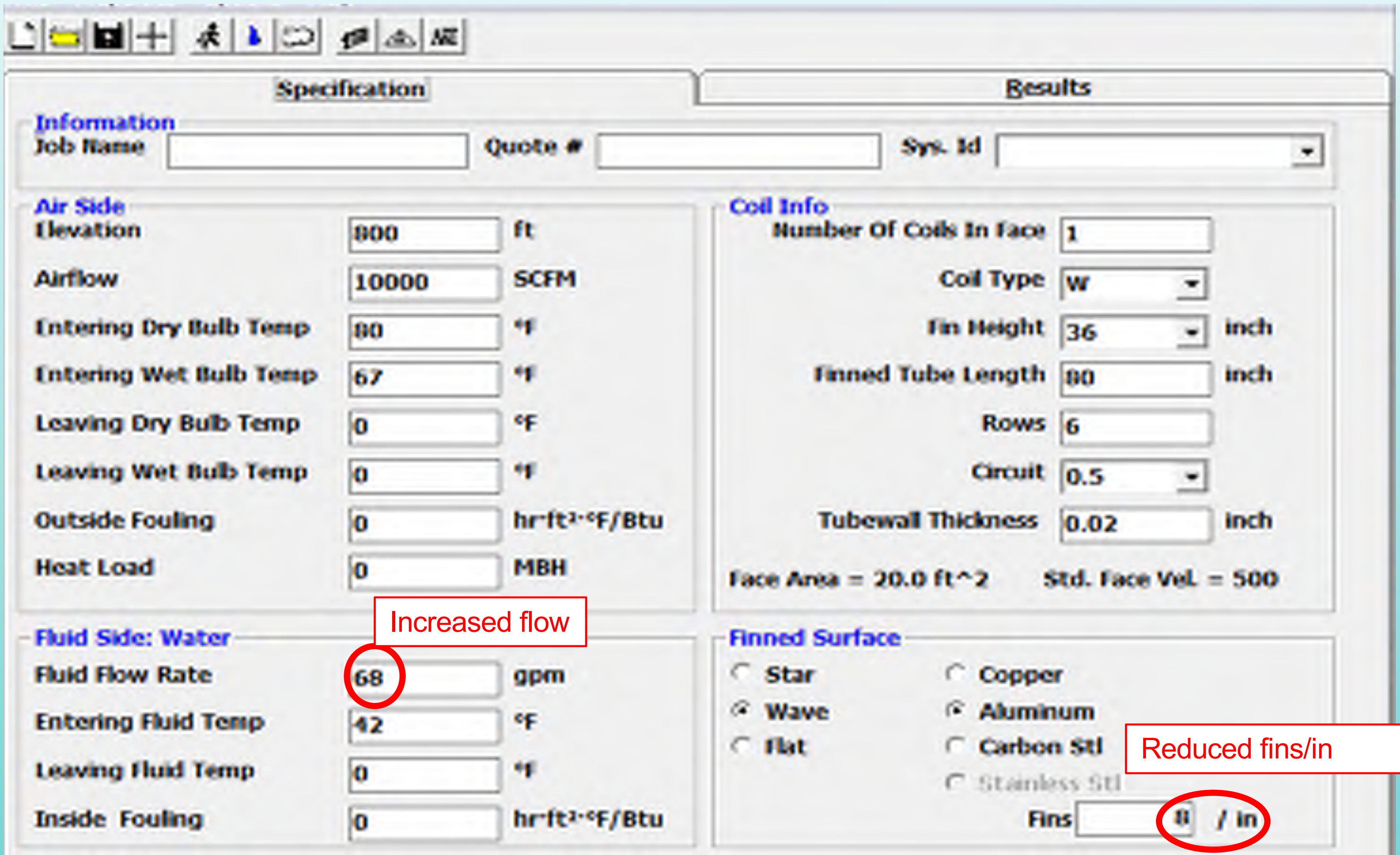
- Airflow, EAT, EWT, water flow Input airflow, EAT, EWT, water flow
- COIL type, coil size
- Select Materials
  - 5/8” x 0.020” thick tubes
  - 6 rows, 10 fins/inch wave pattern
  - 0.006” fin thickness
- Circuiting: Half Circuited

Steps 6 & 7:

- Run results and adjust inputs for desired tube velocities and LATs at 100% and minimum airflow conditions
- Re-iterate as required

Coil Selection Input –

100% Flow Final Selection



Coil Selection

100% Flow Final Selection Output

Specification | Results

System ID	Quantity	TubeFace	CasingHeight inch	NTL inch
	1	24	39.0	80.0

Elevation ft	System Pressure In Hg
800	29.07

Coil Type	W
Fin Material	Aluminum
Tube Wall	0.020
Face Area	20.0

Air Side

Air Flow	Face Velocity fpm	Dry/Wet Temp °F / °F	Outside Fouling hr-ft²-°F/Btu
10000	500	80.0 / 67.0	0.0000

Water Side

Temp °F	Inside Fouling hr-ft²-°F/Btu
42.0	0.0000

Selection Results

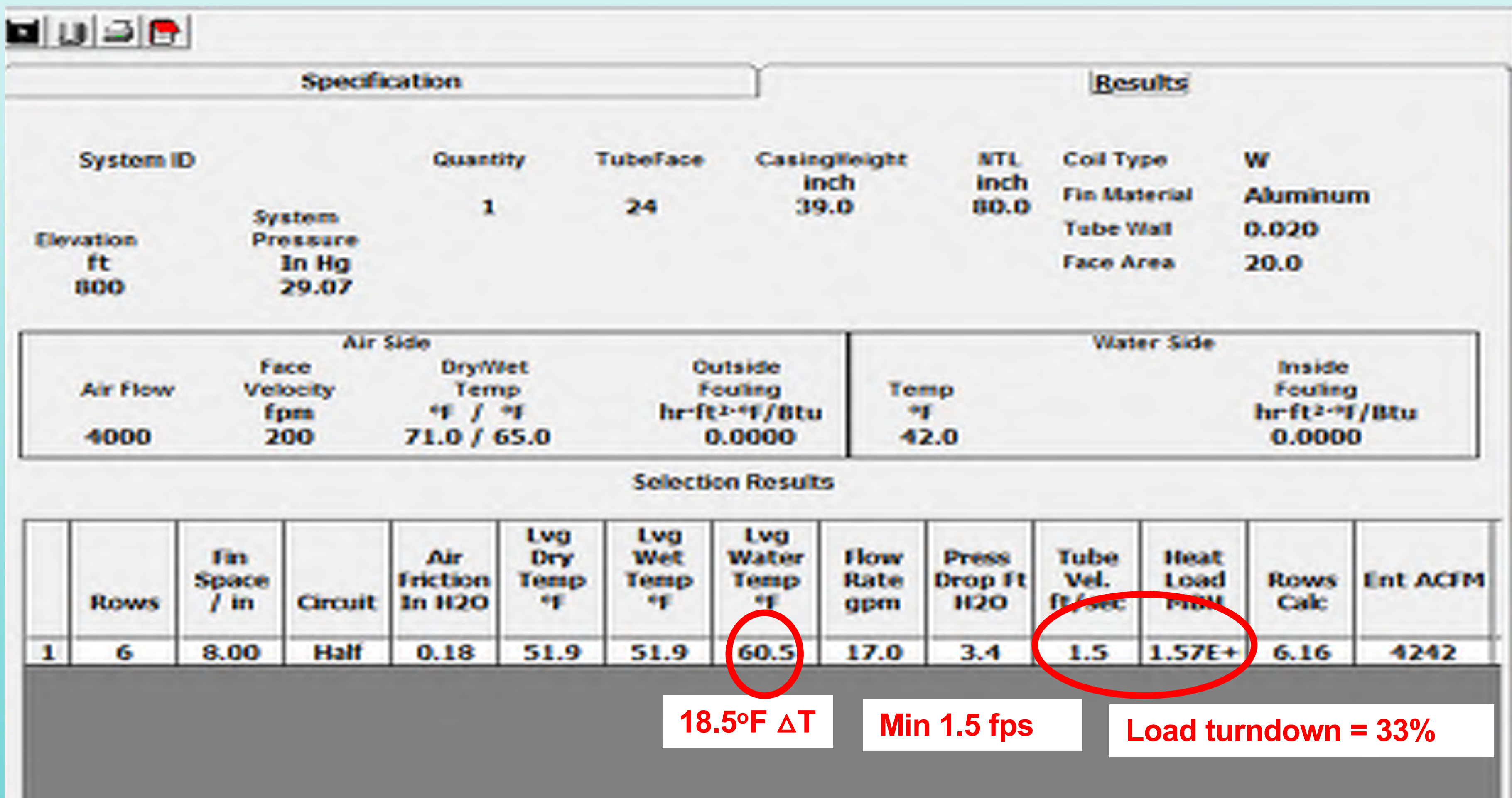
	Rows	Fin Space / in	Circuit	Air Friction In H2O	Lvg Dry Temp °F	Lvg Wet Temp °F	Lvg Water Temp °F	Flow Rate gpm	Press Drop Ft H2O	Tube Vel. ft/sec	Heat Load MBH	Rows Calc	Ent ACFM
1	6	8.00	Half	0.82	52.0	51.6	55.9	68.0	47.9	6.0	4.71E+	6.04	10770

13.9°F ΔT

Max. 6 fps

Coil Selection

40% Airflow and min. tube velocity
Final Selection Output



Specification | Results

System ID	Quantity	TubeFace	CasingHeight inch	NTL inch
	1	24	39.0	80.0

Coil Type	W
Fin Material	Aluminum
Tube Wall	0.020
Face Area	20.0

Elevation ft	System Pressure In Hg
800	29.07

Air Side				Water Side	
Air Flow	Face Velocity fpm	Dry/Wet Temp °F / °F	Outside Fouling hr-ft²-°F/Btu	Temp °F	Inside Fouling hr-ft²-°F/Btu
4000	200	71.0 / 65.0	0.0000	42.0	0.0000

Selection Results

	Rows	Fin Space / in	Circuit	Air Friction In H2O	Lvg Dry Temp °F	Lvg Wet Temp °F	Lvg Water Temp °F	Flow Rate gpm	Press Drop Ft H2O	Tube Vel. ft/sec	Heat Load MBH	Rows Calc	Ent ACFM
1	6	8.00	Half	0.18	51.9	51.9	60.5	17.0	3.4	1.5	1.57E+	6.16	4242

18.5°F ΔT

Min 1.5 fps

Load turndown = 33%

Is there another way to maintain minimum tube velocities without the high pressure drop or Provide minimum tube velocities below 33% load?

- **Coil Selection is Important**
- **Basic Science**
- **Coil Selection**
- **Pumped Coils**

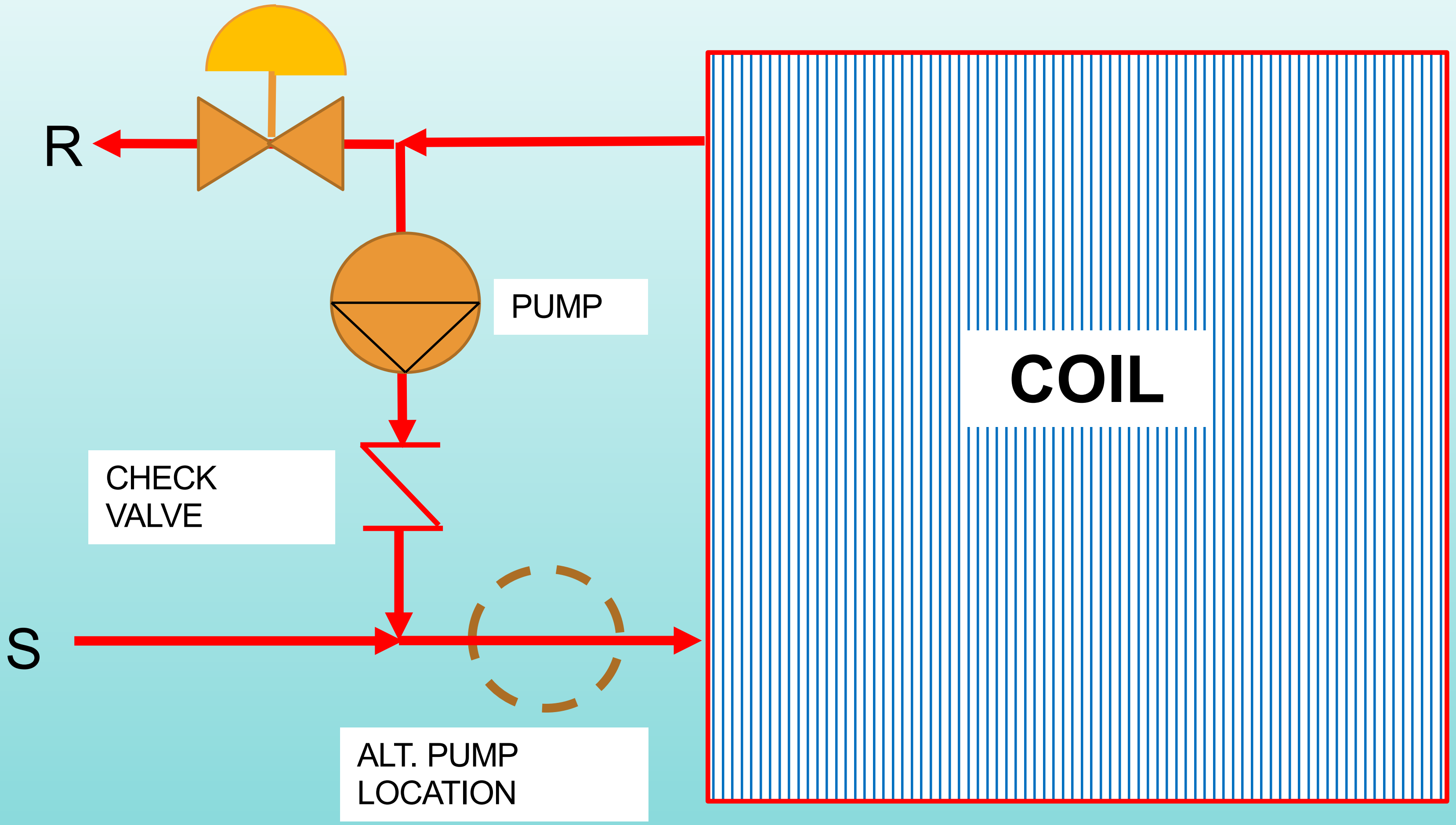
Is there another way to maintain minimum tube velocities without the high pressure drop or Provide minimum tube velocities below 33% load?

YES! USING PUMPED COILS!

Coil pumps can be used to maintain minimum tube velocities, even when system flows vary.

- **Coil Selection is Important**
- **Basic Science**
- **Coil Selection**
- **Pumped Coils**

PUMPED COIL ARRANGEMENT



HOW TO USE PUMPED COILS

<u>Step 1:</u> Select coil size, rows, and circuiting for desired pressure drop at full load conditions

<u>Step 2:</u> Select pump flow based on maintaining minimum tube velocities.

Flow may be higher or lower than full load system flow based on overall system ΔT.

<u>Step 3:</u> With flow and circuiting fixed, select coil fins and EWT to meet desire full load performance.

HOW TO USE PUMPED COILS

<u>Step 4:</u> Use mixing equation to determine overall system flow, LWT, and ΔT.

<u>Step 5:</u> Select control valve based on system flow, not coil flow.

PUMPED COIL CONTROL

$Q\ (BTUH) = U \bullet A \bullet LOG(\Delta T / \Delta T)$

- U is fixed by maintaining tube velocity
- Area is fixed by selecting coil size, tubing, and circuiting
- Capacity is controlled by varying the $LOG(\Delta T / \Delta T)$ or blending water temperatures up/down.

MIXING EQUATION

SYSTEM ENERGY = COIL ENERGY

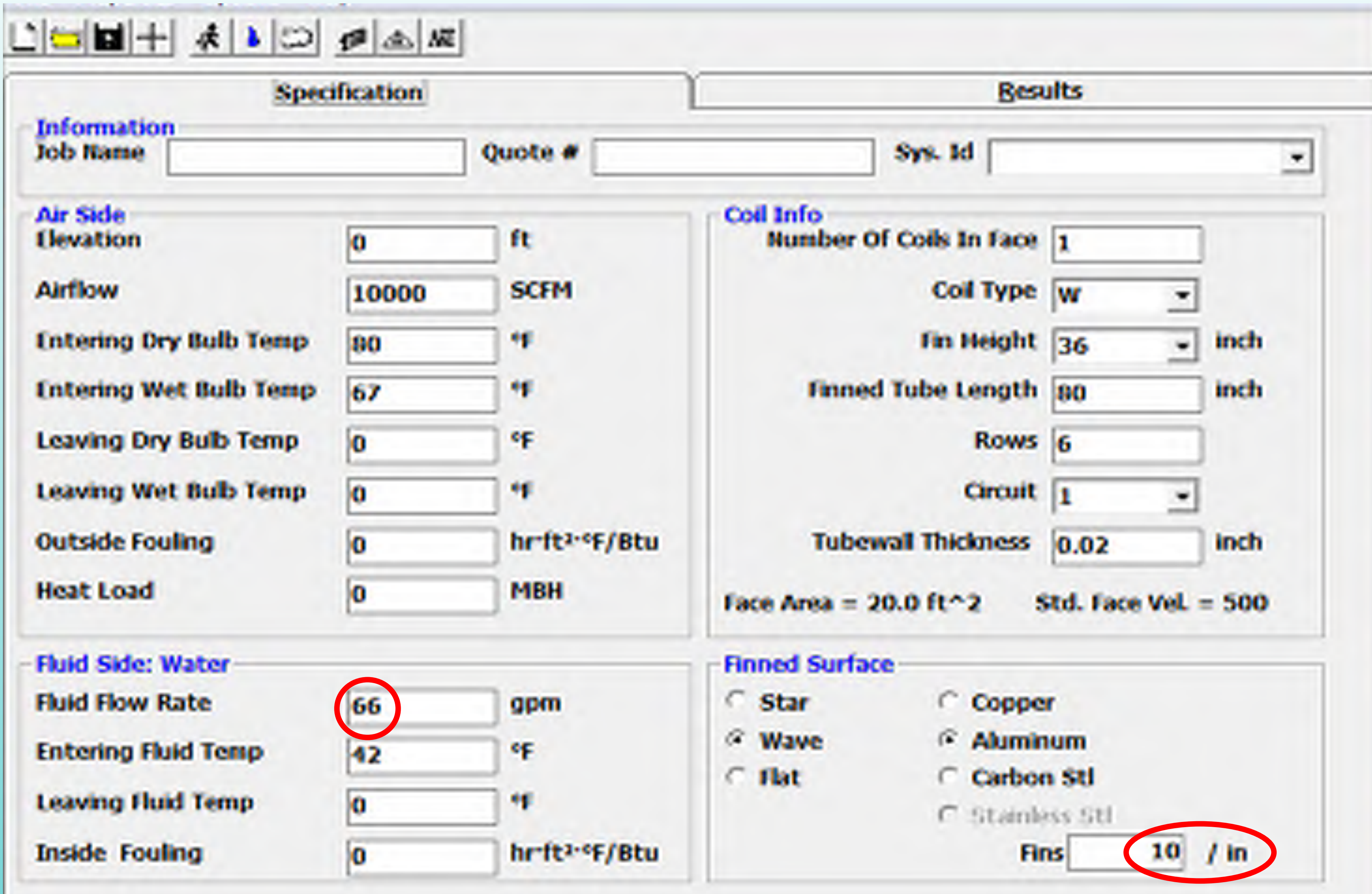
$Q_{sys} = GPM_{sys} \bullet \mathbf{500} \bullet (T_{sys\ in} - T_{sys\ out})$

$Q_{coil} = GPM_{coil} \bullet \mathbf{500} \bullet (T_{coil\ in} - T_{coil\ out})$

$T_{coil\ out} = T_{sys\ out}$

$$\mathbf{GPM_{sys} = GPM_{coil} \frac{(T_{coil\ in} - T_{coil\ out})}{(T_{sys\ in} - T_{coil\ out})}}$$

SAMPLE COIL SELECTION



SAMPLE COIL SELECTION @ 100% LOAD

Specification | Results

System ID	Quantity	TubeFace	CasingHeight inch	NTL inch
	1	24	39.0	80.0

Coil Type	W
Fin Material	Aluminum
Tube Wall	0.020
Face Area	20.0

Elevation	System Pressure In Hg
Sea Level	29.92

Air Side

Air Flow	Face Velocity fpm	Dry/Wet Temp °F / °F	Outside Fouling hr-ft²-°F/Btu
10000	500	80.0 / 67.0	0.0000

Water Side

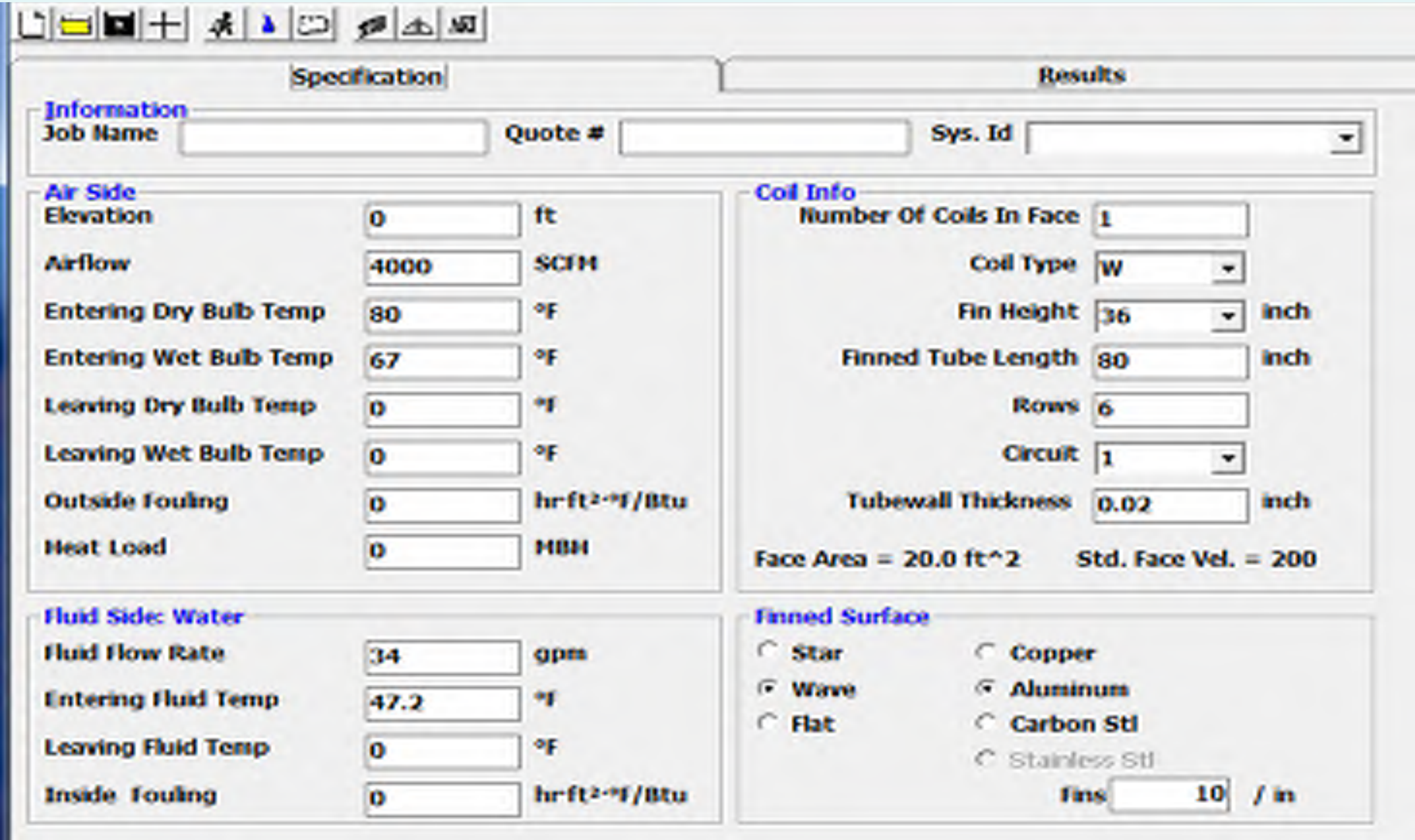
Temp °F	Inside Fouling hr-ft²-°F/Btu
42.0	0.0000

Selection Results

	Rows	Fin Space / in	Circuit	Air Friction In H2O	Lvg Dry Temp °F	Lvg Wet Temp °F	Lvg Water Temp °F	Flow Rate gpm	Press Drop Ft H2O	Tube Vel. ft/sec	Heat Load MBH	Rows Calc	Ent ACFM
1	6	10.00	Full	0.91	52.0	51.8	55.8	66.0	6.4	2.9	4.55E+	6.04	10453

SAMPLE COIL INPUT

FOR 40% LOAD



SAMPLE COIL SELECTION

FOR 40% LOAD

Pump ON with loads below 40%

Specification | Results

System ID	Quantity	TubeFace	CasingHeight inch	NTL inch
	1	24	39.0	80.0

Elevation	System Pressure In Hg
Sea Level	29.92

Coil Type	W
Fin Material	Aluminum
Tube Wall	0.020
Face Area	20.0

ADJUSTED EWT TEMP TO 47.2°F GET 52°F LAT

Air Side				Water Side	
Air Flow	Face Velocity fpm	Dry/Wet Temp °F / °F	Outside Fouling hr·ft²·°F/Btu	Temp °F	Inside Fouling hr·ft²·°F/Btu
4000	200	80.0 / 67.0	0.0000	47.2	0.0000

Selection Results

	Rows	Fin Space / in	Circuit	Air Friction In H2O	Lvg Dry Temp °F	Lvg Wet Temp °F	Lvg Water Temp °F	Flow Rate gpm	Press Drop Ft H2O	Tube Vel. ft/sec	Heat Load MBH	Rows Calc	Ent ACFM
1	6	10.00	Full	0.21	52.0	51.9	57.9	34.0	1.8	1.5	1.81E+	6.24	4181

34 GPM IS PUMP FLOW VS 66 GPM FOR 100% FLOW

ADJUSTED FLOW TO GET 1.5 FPS TUBE VELOCITY

WHEN TO USE PUMPED COILS

- **Use pumped coils when**
  - When precise temperature control is required throughout full operating range (below $\pm$33% load).
  - Precise temperature zones (<$\pm$0.5^{O}F)
  - Preheat coils when EAT is < 32^{o}F

NOTE – Increased flow and tube velocity can be achieved without pumps by adjusting EWT UP.

CONCLUSIONS

- Be aware of system turndown and no. of hours at part load conditions
- Be aware of minimum tube and coil face velocities
  - Avoid high concentration of glycols for cooling coils
- Coils can be picked for 4:1 turndown at best
- Pumped coils are a good option to maintain tube velocities at low loads

QUESTIONS?
Discussion

GENE NELSON, PE
gcnelson65@gmail.com