Impact of Web Permeability on High Speed Web Transport

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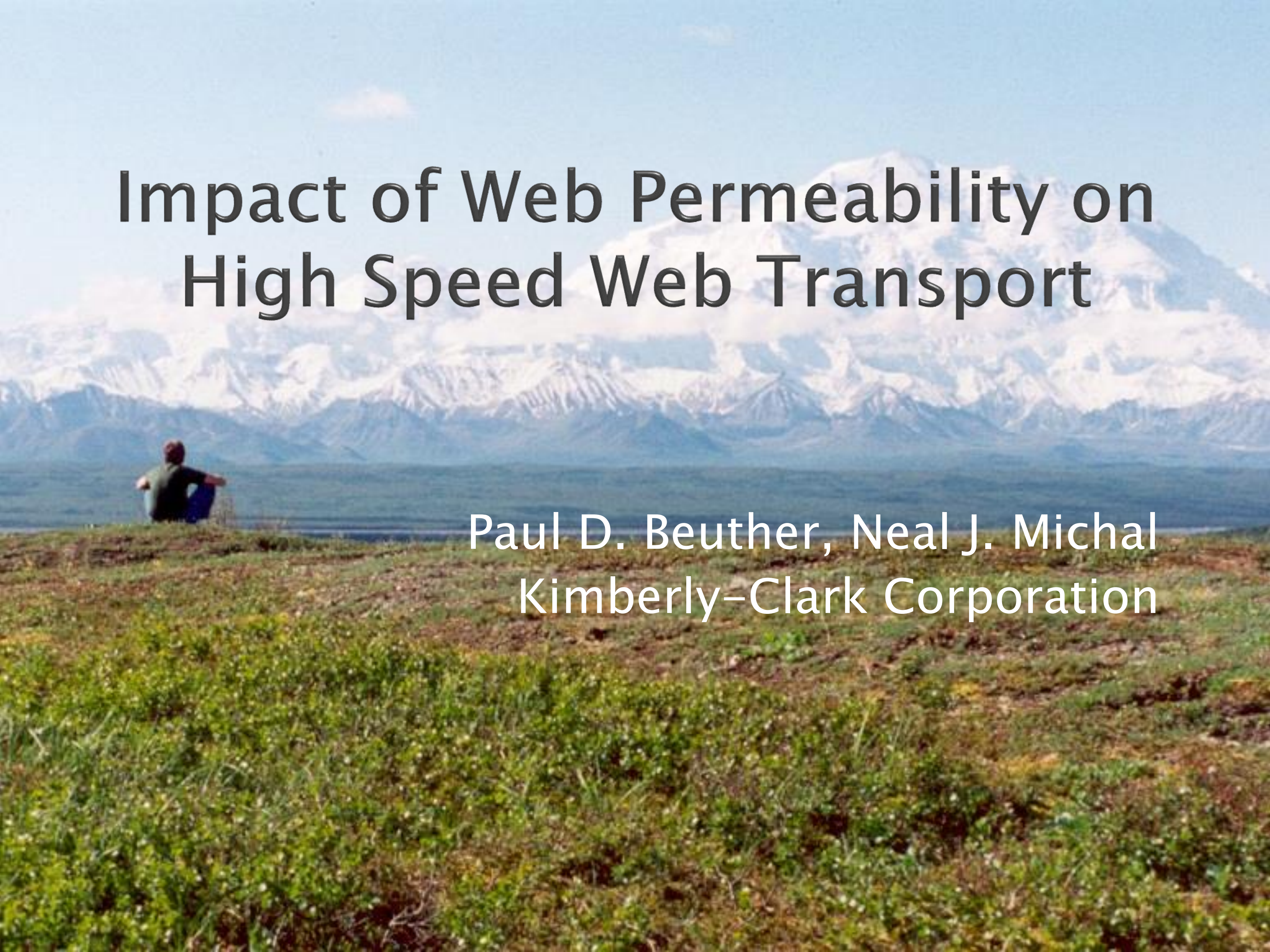


Relevance to Web Handling

- Turbulent air drag is the dominant source of tension loss at high web speeds. It is related to several things:
  - Web Velocity: $\sim V^2$
  - Surface area of the moving web: Length x Width
    - Surface roughness of the web
    - Web Flutter
    - Distance between web and other web or wall
  - New finding – Very large 3-4X non-linear relationship with web permeability!

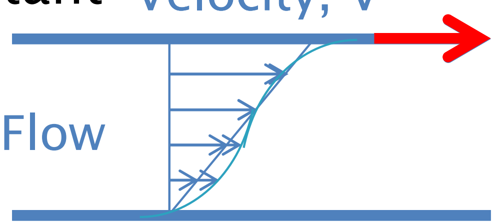
Background of Problem

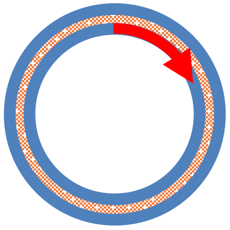
- Michal first reported the large tension loss through a festoon at IWEB 2009. Beuther related this to air drag and web permeability in 2013 at the APS Division of Fluid Dynamics meeting
- Published literature data about drag in turbulent boundary layers with permeable walls is very sparse
  - Most studies deal with forced aspiration or suction, and usually a single-sided system
- Direct Numerical Simulation studies by Jimenez and later Quadrio showed some effect, but not as strong as our data shows

Experimental Approach

- Festoon used to study air drag due to long web length and compact size
  - Series of plane turbulent Couette flows between webs
- Much laboratory Couette flow data from studies using concentric rotating cylinders
  - Impossible to study permeable walls
- Advantages and disadvantages of using a festoon
  + Provides a stable planar Couette flow between the multiple moving webs
  + Easy to vary the area of the web being measured
  + Relevant to many web handling applications

  – Potential for interaction between web spans
  – Edge effects can be important



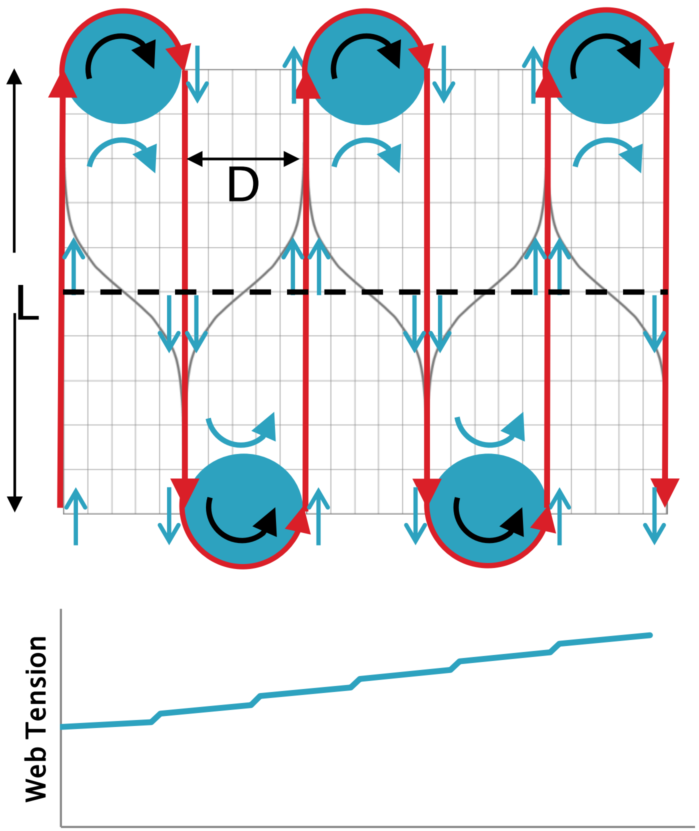


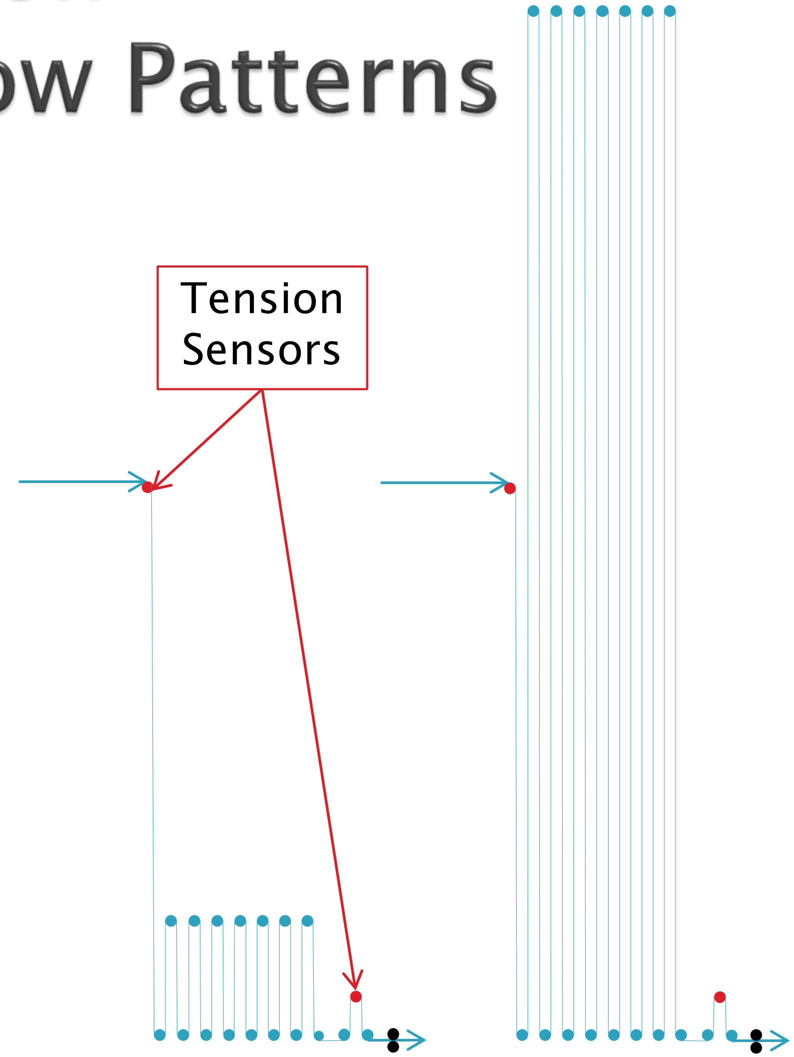
Experimental Facilities

- Two different festoons
  1. Small 0.4 m wide festoon, 30 mm web spacing
  2. Large 3.2 m wide festoon, 165 mm spacing
- Tension load cells at entrance and exit of festoon
- Studied several non-wovens with different permeability at various web tensions and speeds.

Web Path in a Festoon
Multiple Couette Flow Patterns

Turbulent air flow pattern in a festoon
(Not to scale)





Normal Run Position
10:1 length/gap

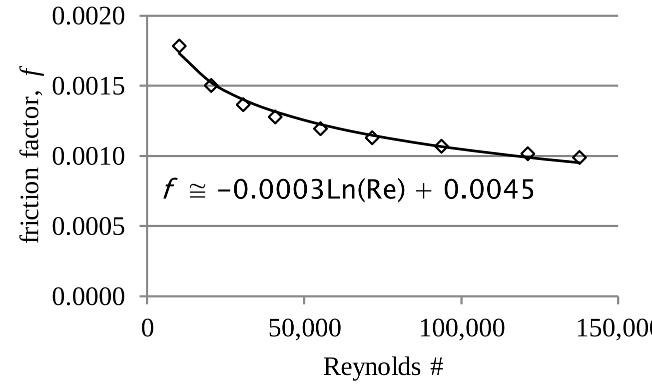
Splice Position
>60:1 length/gap

Empirical Couette Drag Estimates

- Historical data from concentric cylinders for fully developed steady turbulent flow

Wall Shear Stress, $\tau_w = f\,\dfrac{\rho V^2}{2}$

$$\frac{1}{\sqrt{f}} = 8.13\ \mathrm{Log}_{10}\left(Re\sqrt{\frac{f}{2}}\right) + 3.49$$



(DORFMAN, L. A. 1963. “Hydrodynamic resistance and the heat loss of rotating solids”, Edinburgh, Oliver and Boyd.)

Because the ratio of cylinder circumference to gap is large, the results from the circular cylinder Couette flow are directly applicable to the planar Couette flow of a festoon

Relation to Flow in Festoon

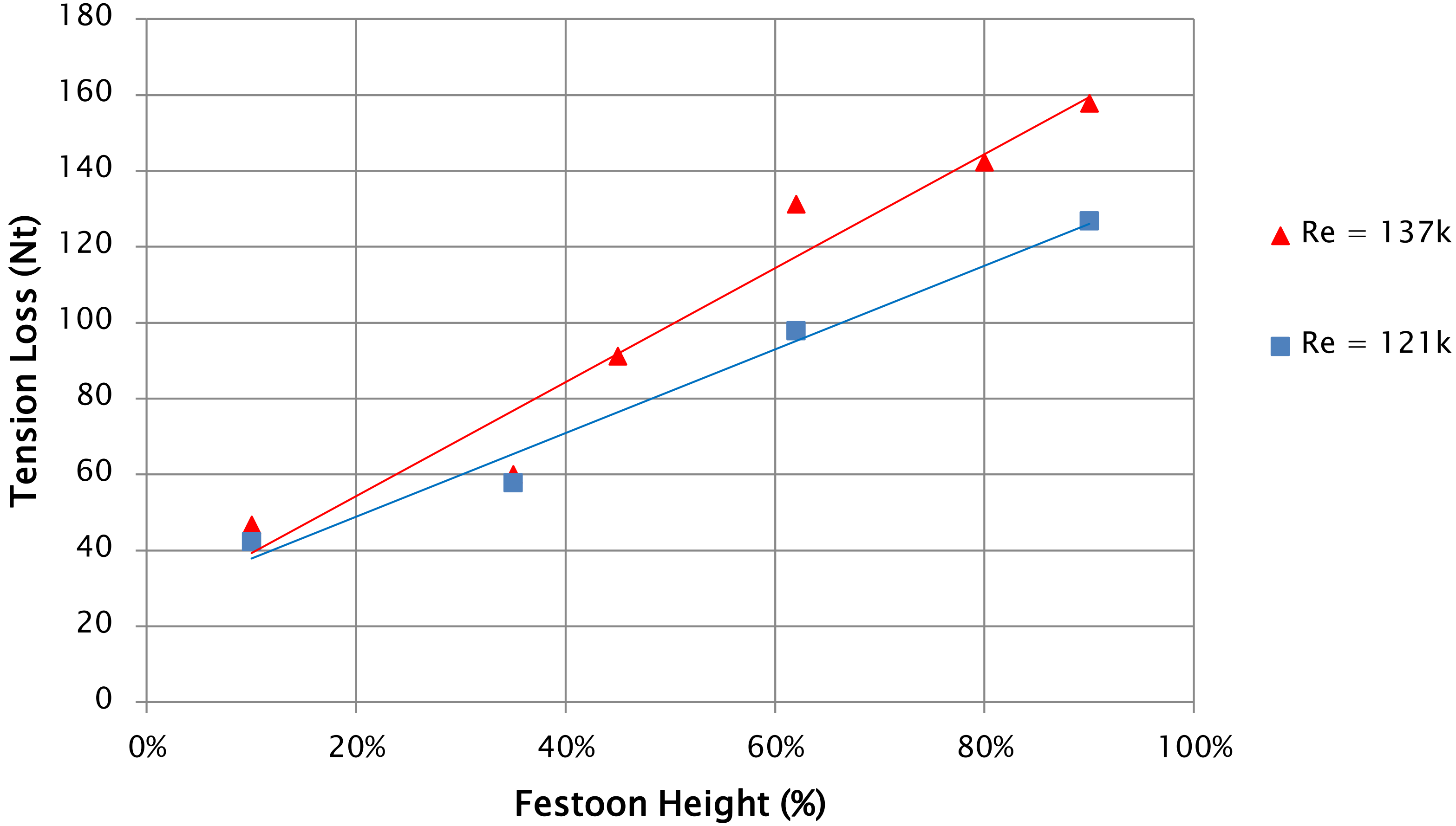
- Air Drag (Tension Loss) = τ_w * Length * Width * 2
  - Factor of 2 because of drag acts on both sides of the moving web
- $\tau_w = f\frac{\rho V^2}{2}$; $f \cong -0.0003\ \mathrm{Ln(Re)} + 0.0045$
- $Re = \frac{2\rho DV}{\mu}$; ρ=air density, D=Spacing, $V = V_{web}$, μ=dynamic viscosity
  - Factor of 2 because both webs are moving in opposite directions – Relative velocity = twice web velocity.

- Calculating τ_w for two festoon examples using Dorfman's empirical relationship yields:
  - 6.35 m/s, 3.2 m wide,165 mm gap, est. τ_w = 0.10 Nt/m^2
  - 10 m/s, 0.25 m wide, 30 mm gap, est. τ_w = 0.32 Nt/m^2
    - The second case was also confirmed through CFD simulation

Measuring Air Drag in a Festoon

- Run at a steady speed, then change the festoon carriage height to a different height
  - The only thing that changes is the amount of area of web in the center portion of the festoon. All other forces are constant for all festoon heights
    - Bearing Drag
    - Entrance and Exit effects of festoon
    - Entrance air drag and entrance effects of each roller
- Plot Tension Loss vs Height
  - The Slope relates linearly to the wall shear stress τ_w
  - $\tau_w = \frac{1}{2nw} \frac{\Delta Tension\ Loss}{\Delta H}$; $n = \#\ of\ webs, w = web\ width, H = festoon\ height$
  - Intercept of Tension Loss vs. Height relates to bearing drag, entrance effects, and drag outside of festoon

Tension Loss Data for Large Reynolds # Festoon at 6.35 and 5.6 m/s



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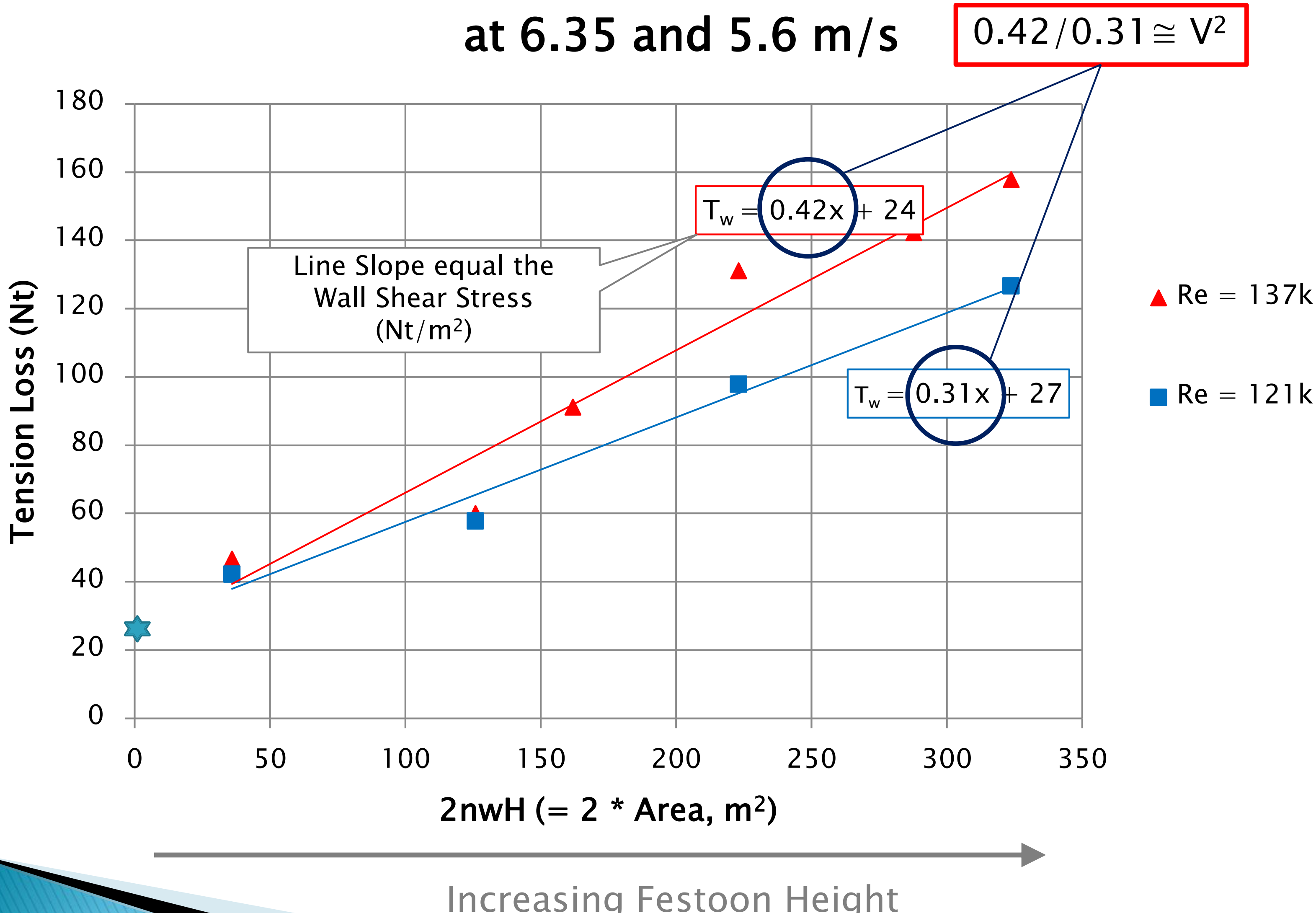

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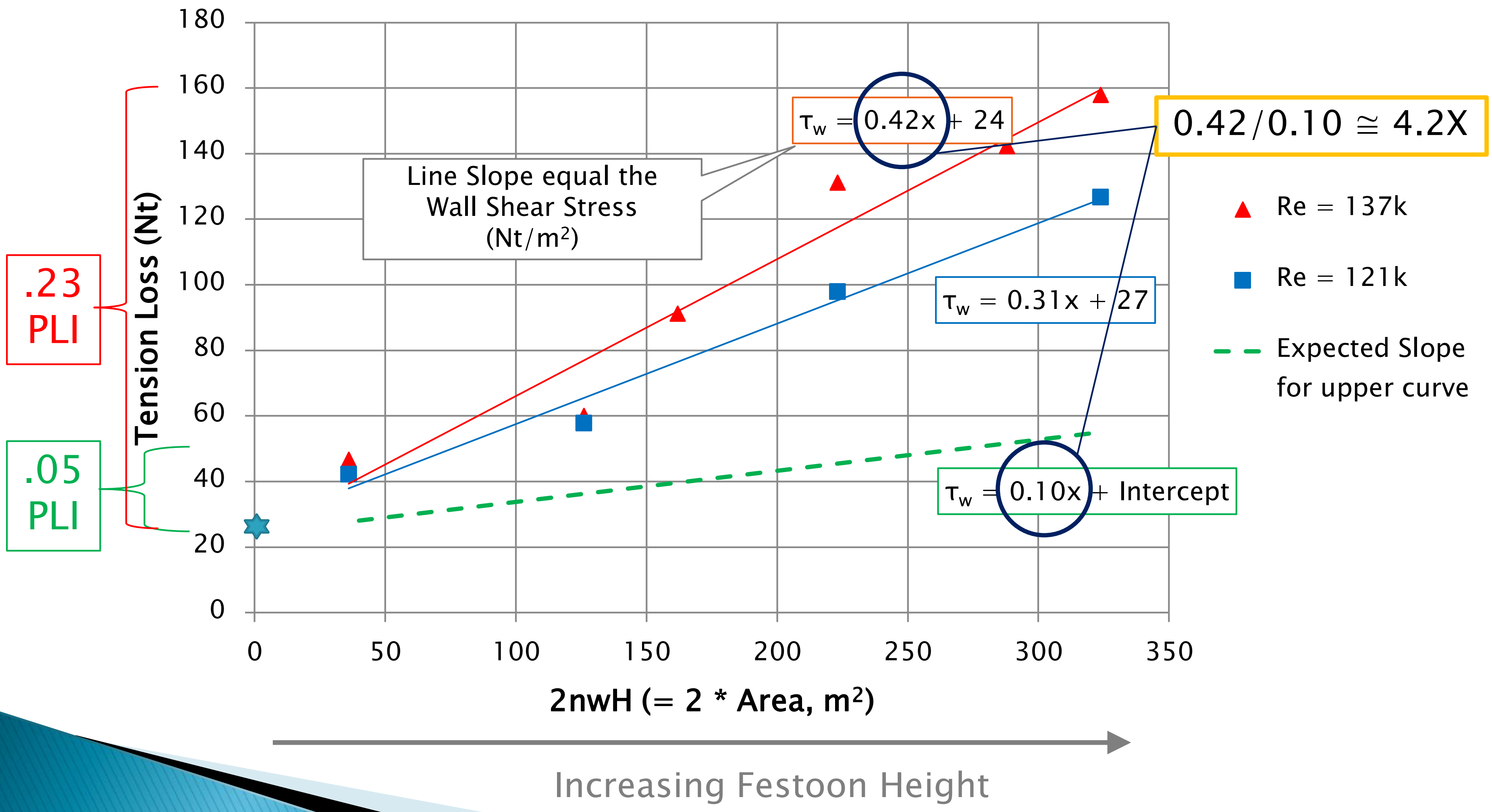
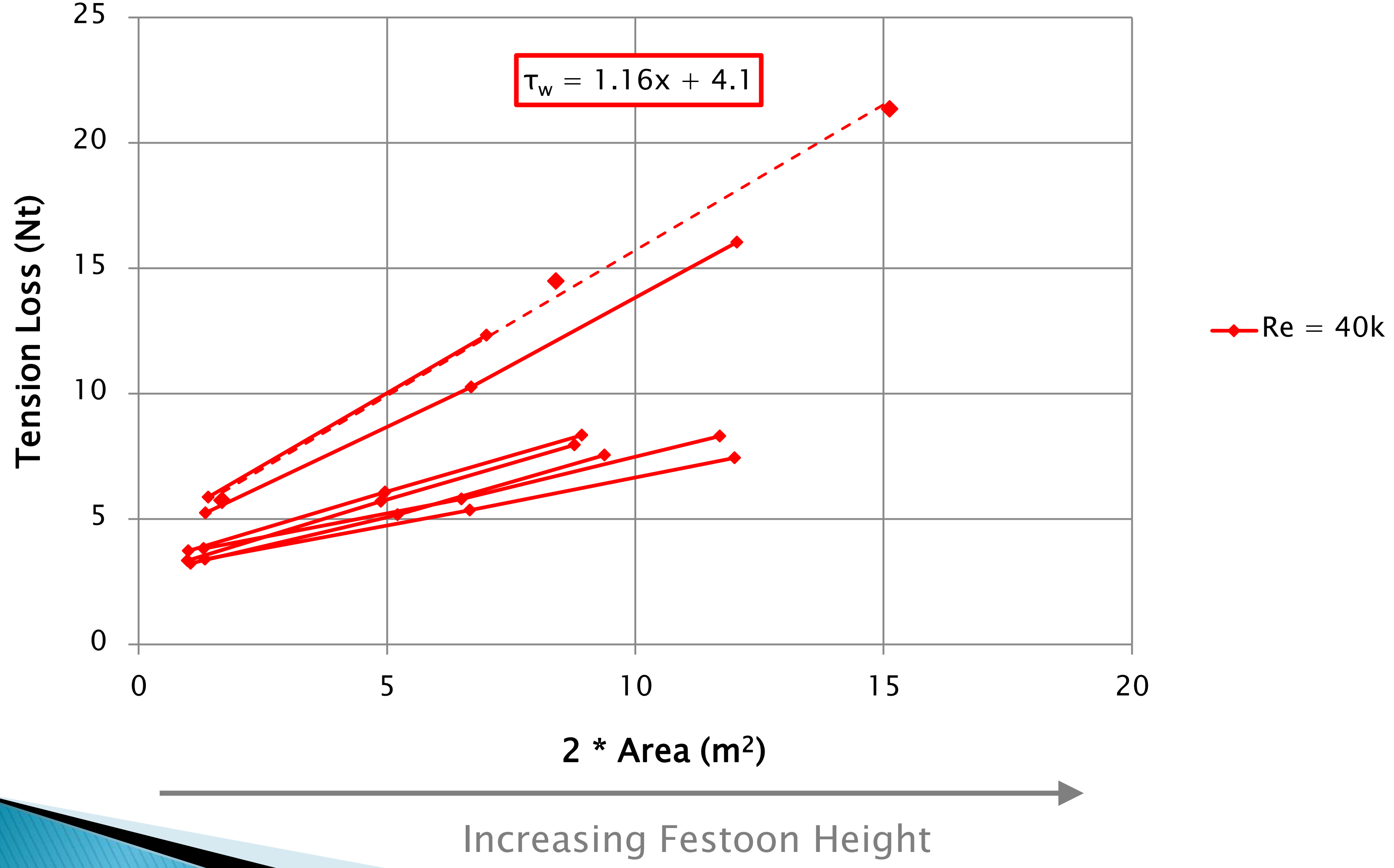


Materials Studied

Material	Type	Air Perm ($m^3/s/m^2$)	BW (g/m^2)
1	Film/SB	0	30
2	Film	0	16
3	SB/MB	2.40	14
4	SMS	2.70	6
5	SB/MB	2.80	12
6	SB	3.20	12
7	SB	3.30	14
8	SB	3.50	15.3
9	SB	3.90	14
10	SB	4.20	20.3
11	SB	4.40	17.5
12	SB	4.80	14
13	SB	5.09	15.3
14	SB	5.13	17.5
15	BCW	5.50	22
16	SB	5.60	8

Air Permeability was determined by measuring the volumetric air flow through a material under a pressure difference of 125 Pa (½ inch H_2O).

Tension Loss Data for Low Reynolds # Festoon with Eight Materials



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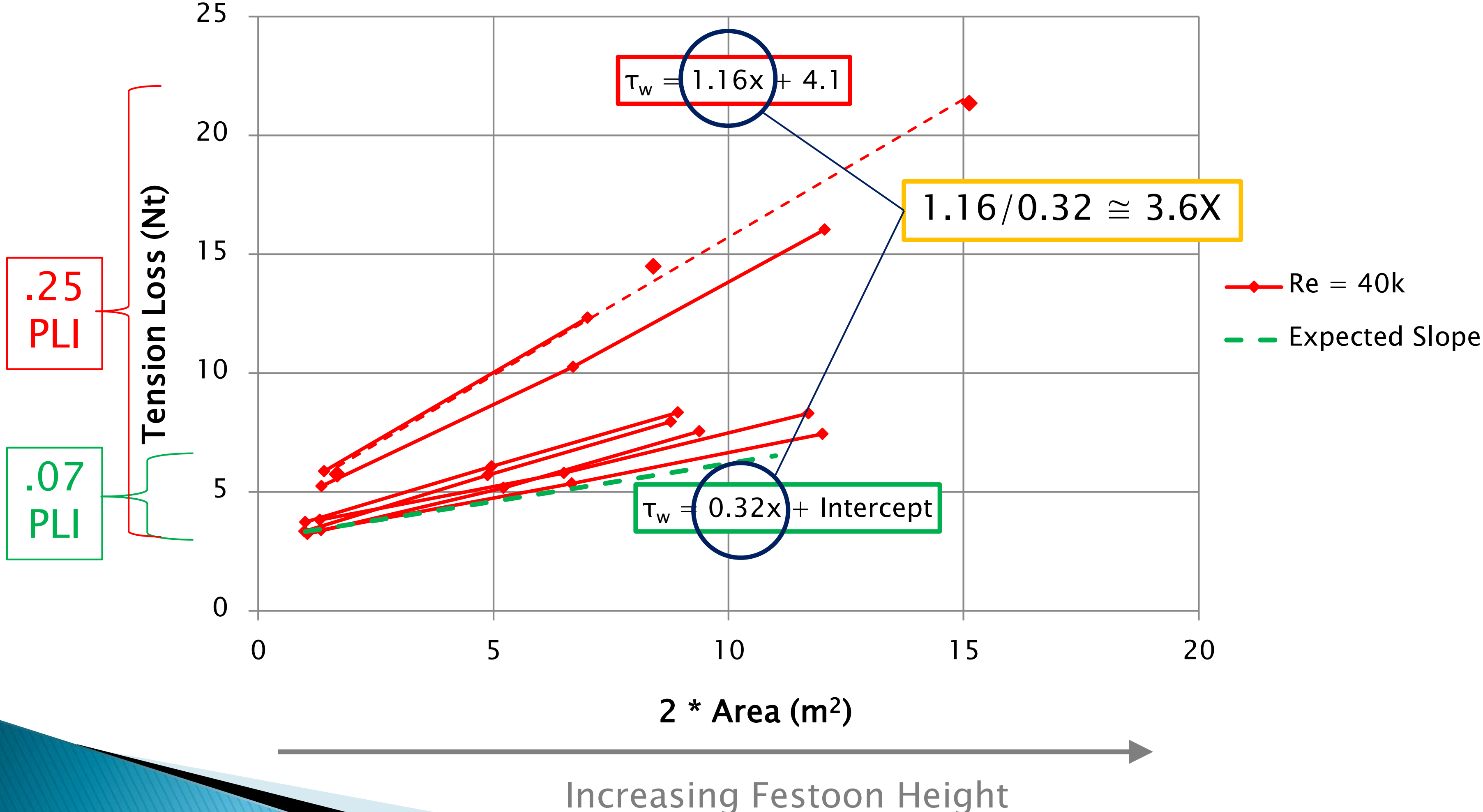
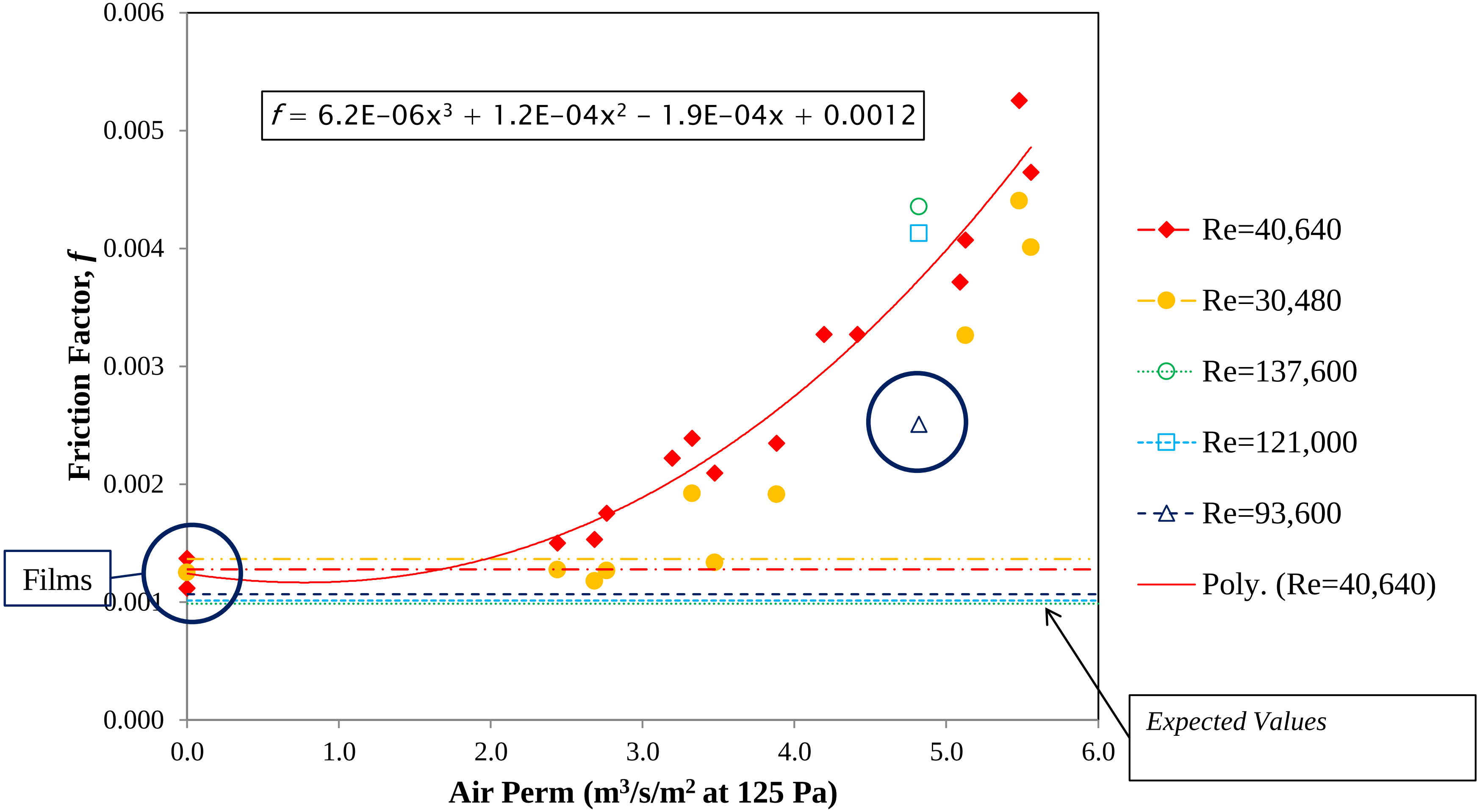
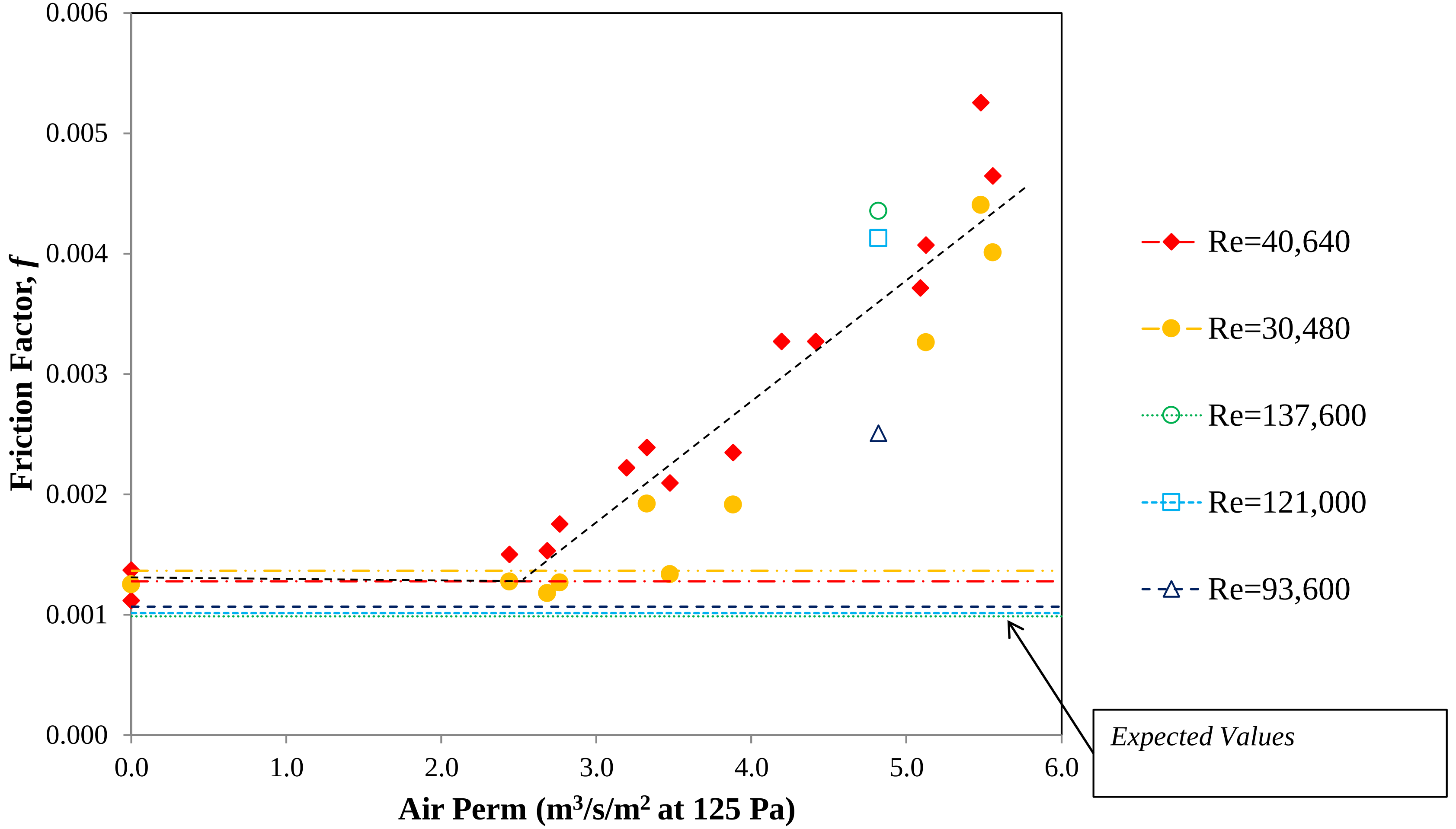


Measured Friction Factor in Turbulent Plane Couette Flow for Permeable Webs



Alternative Response Relationship



Research Hypotheses, Future Needs

- We hypothesize that high web permeability allows for a large transport of turbulent energy from one flow stream to another.
- The coupling of flows in adjacent air streams likely play a large roll in the air drag increase

- Mechanism for the increase is still unknown – Flow studies to help understand the mechanics need to be conducted
  - PIV measurements
  - Flow visualization
  - Wind tunnel studies on a porous flat web
  - CFD free from conventional boundary layer models
  - More webs in the 1–2 $m^3/s/m^2$ permeability range need to be studied at a wider range of Reynolds #

Summary

- Past studies of the impact of air permeability focused on air lubrication on rollers from impermeable webs.
- This study aims at the high permeability range
  - Air Drag increases in a highly-non-linear fashion with air permeability, up to 4X that of a non-permeable web.
  - There may be a threshold limit for air permeability
  - The impact on web tension loss can be severe!
  - Industry trends are to run lighter, more porous webs at higher speeds
- Web air permeability is a key parameter for web handling dynamics at high speeds.

Questions?