Enabling low-emission LNG systems

Flow pattern transitions and hysteresis effects of falling film over horizontal tubes

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Motivation

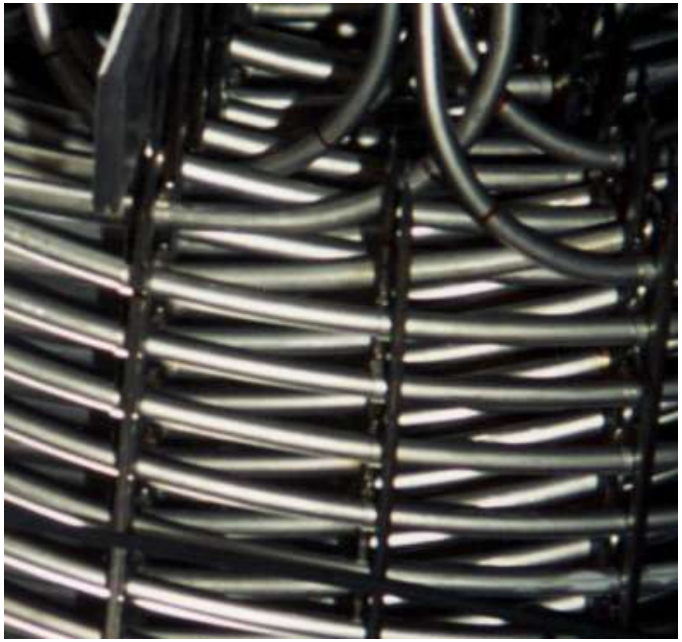
- Purpose of work
  - To gain insight into fundamental phenomena occurring in heat exchangers of natural gas liquefaction plants.
- Basic hypothesis
  - A thorough understanding of the processes and phenomena occurring at a small-scale level in the heat exchanger is necessary to improve heat exchangers' design and operation
- This task
  - To characterize flow regimes between the tubes.
  - The heat transfer is decided by film thickness, the stability and thickness of the film is depending on flow type between the tubes

Spiral heat exchanger

Photo: Linde Group

Spiral wound HX – flow between tubes

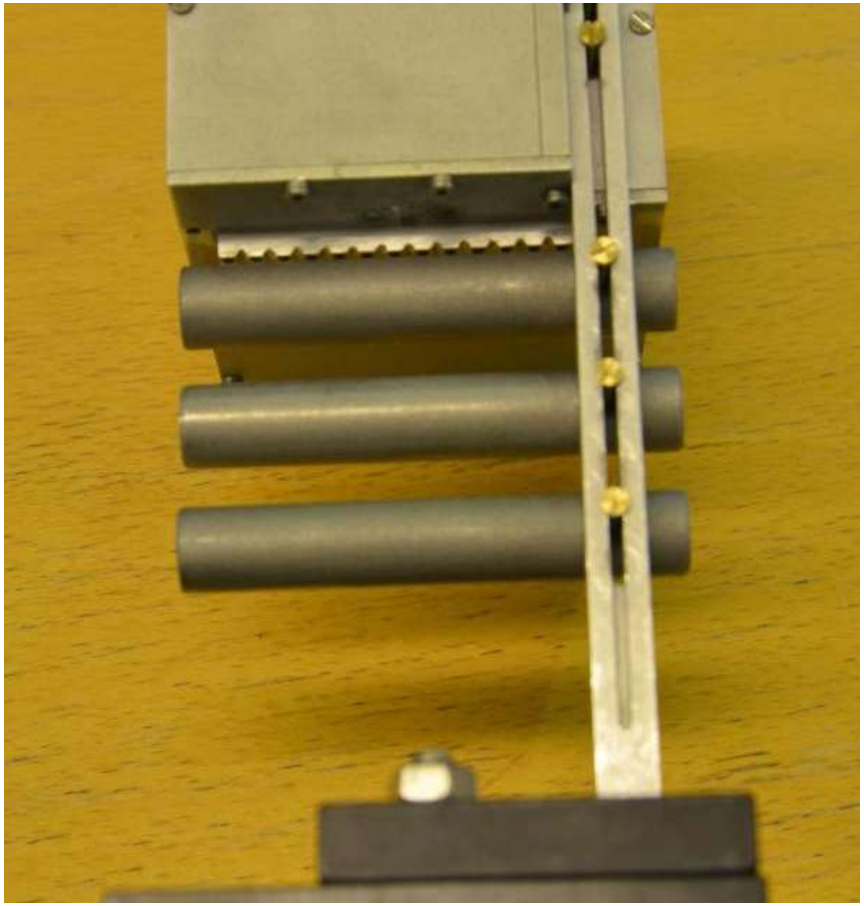
- In a spiral wound HX, the tubes are at an angle and supported regularly.
- The flow will partly go along the tubes and fall down at the supports
- Typically the tubes are quite close
- Our goal: Understand flow between tubes
- Experimental model
  - Horizontal tubes
  - Flow would otherwise go to the end of tubes
- The image is actually of a spiral wound HX for a reactor
  - In an LNG heat exchanger the tubes are closer together



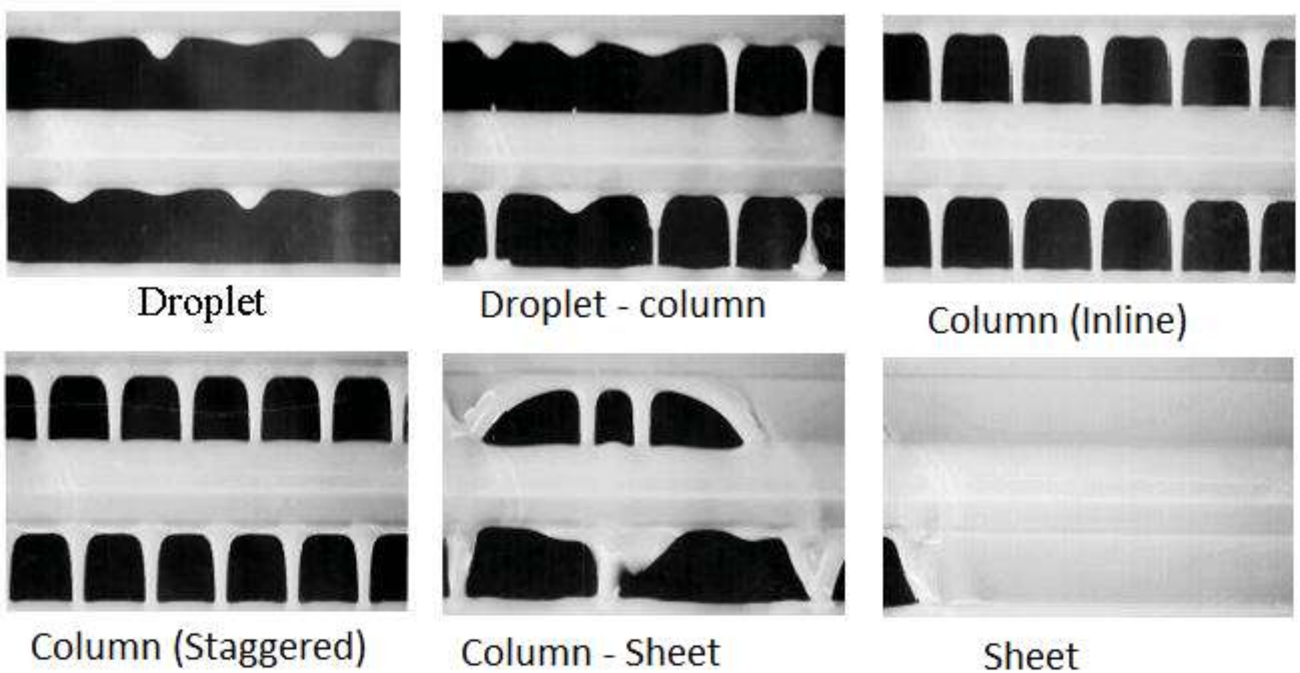
Experimental setup

- A reservoir over a drip hole arrangement
- Even flow onto the upper tube.
- Flow is captured by a high speed camera
- In the setup
  - Tube diameter
  - Tube distances

  can be varied
- The surface of the tubes is rough



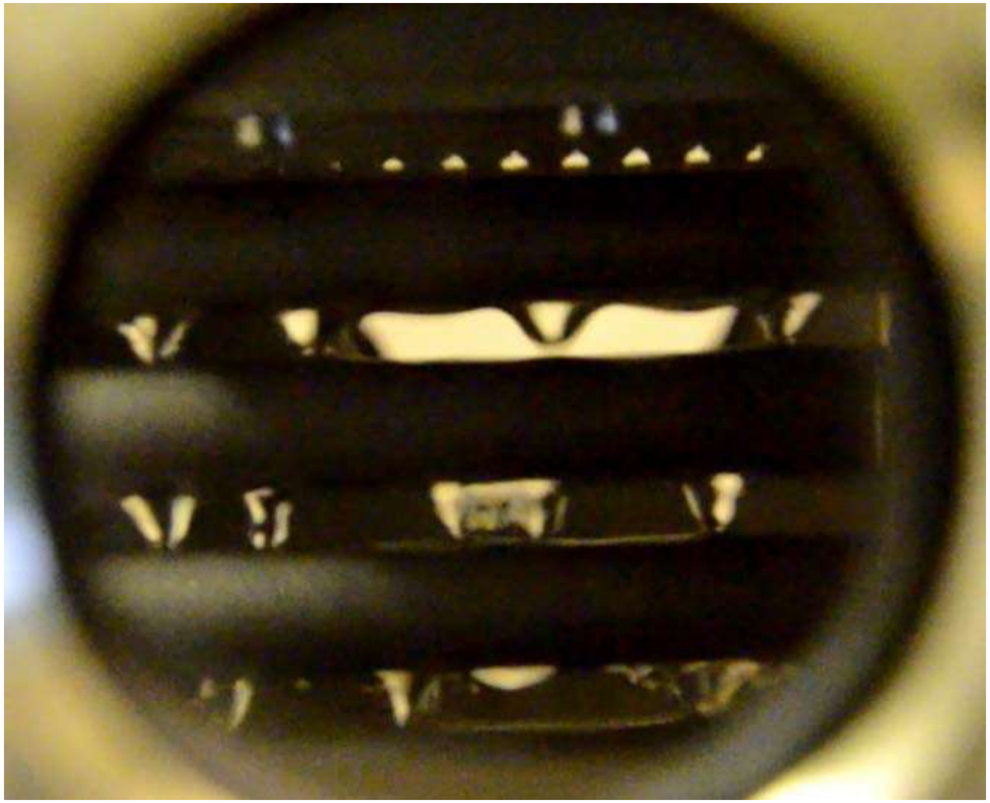
Flow pattern categorization



Hu & Jacobi 1996[1]

- There are additional transitional / hybrid states
- Between tubes with pentane the flow regimes could be less defined than in illustration

Droplet mode with 4 mm spacing



Analysis

- Important variables that decides behaviors:

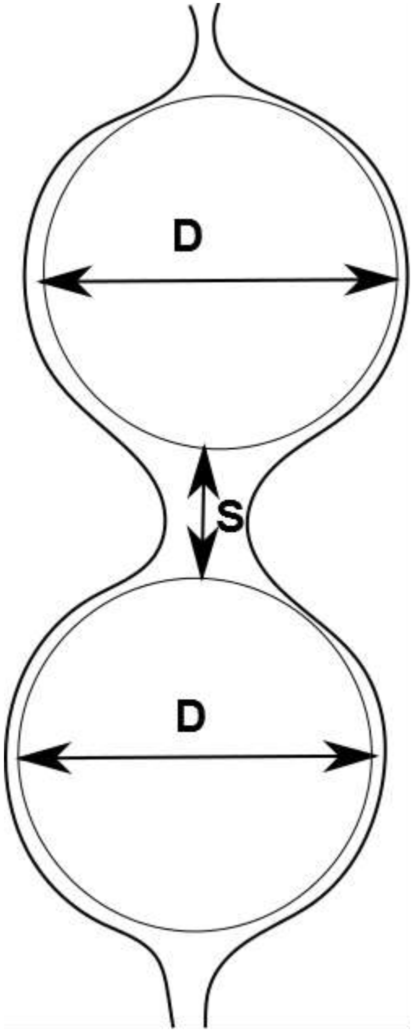
  ρ_l: Density liquid (kg/m^3), σ: Surface tension (N/m)
  μ: Viscosity(Ns/m^2), g: Gravity($= 9.81m/s^2$)
  D: Tube diameter(m), S: Space between the tubes(m)
  Γ: Flow/Tube length (kg/ms), k: Roughness(m)

- Characteristic length of surface tension:
  - $Ca = \sqrt{\sigma/(\rho g)}$
- 5 dimensionless parameters (Dimensions m, s, kg, 8-3=5):

$$Re = \frac{2\Gamma}{\mu_L}, \quad Ga = \frac{\rho_L \sigma^3}{\mu_L^4 g}, \quad \frac{D}{Ca}, \quad \frac{S}{Ca}, \quad \frac{k}{Ca}$$

- The following parameter can be made without viscosity:

$$\frac{Re}{Ga^{1/4}} = \frac{2\Gamma g^{1/4}}{\rho_L^{1/4} \sigma^{3/4}}$$



Model

- Must author uses the following model for the transitions:

$$Re = A \times Ga^{p}$$

  - Often p = 0.25, and it is always close to 0.25
- Some (like Jacobi, 2012 [6]) also uses:

$$Re = A \times Ga^{1/4}\sqrt{S/Ca}$$

  - Bases: minimum energy for a long column or sheet

Uncertainty

- The flow regime characterization is subjective.
- Uncertainty in mass flow, fluid properties and dimensions.
- To check repeatability, two measurement series are done under the same conditions, D=12mm and space between tubes (S) of 3 mm (S/Ca = 2.0)
  - Deviation between these two experiments in $Re/Ga^{1/4}$ become 0.040
- Tubes in Heat exchanger usually close together: Harder to identify flow regime

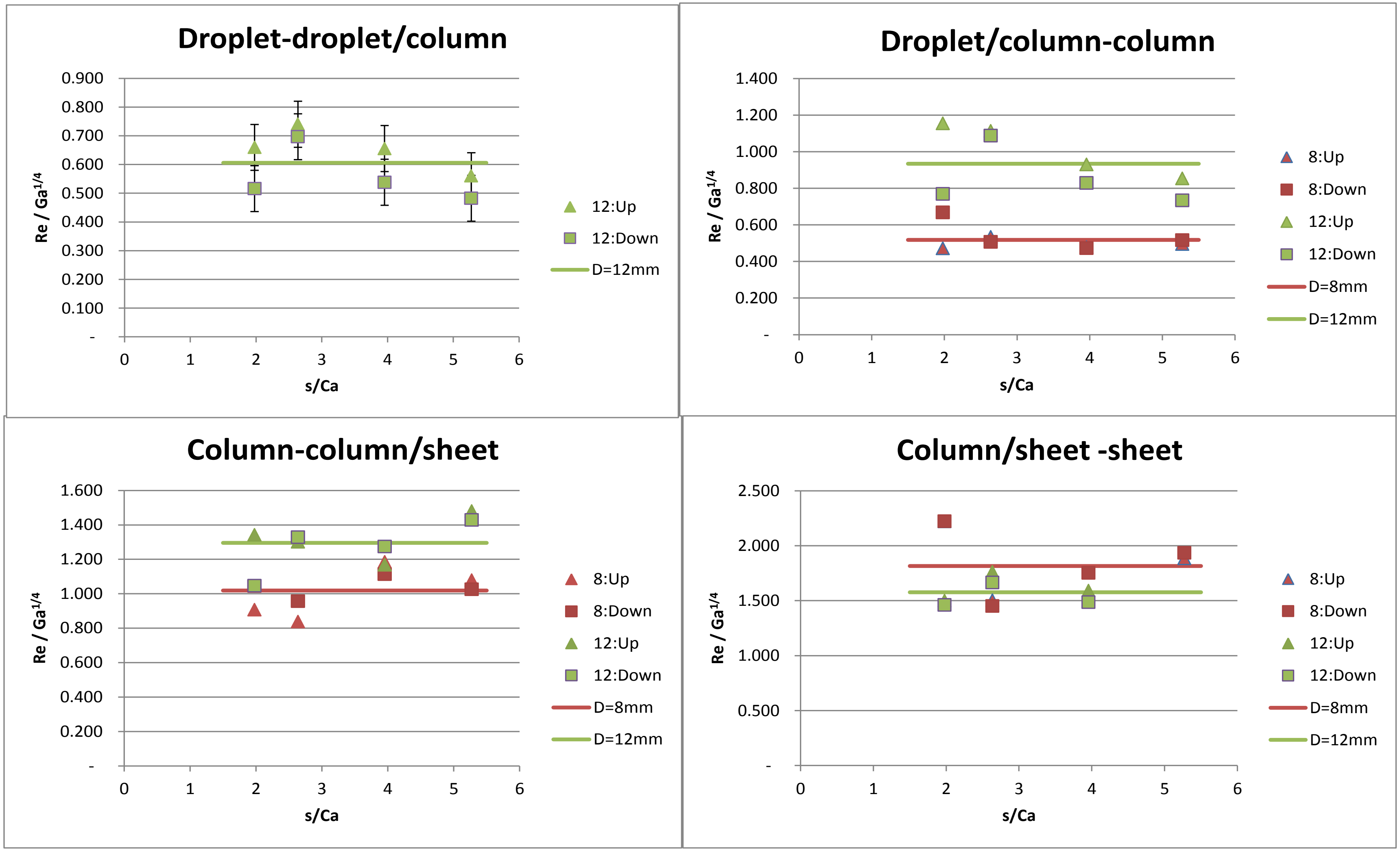
Flow characteristics of pentane

- Like natural gas, pentane has:
  - Low surface tension
  - Low viscosity

  compared with water

	Pentane (40°C)	**Liquid methane (-162 °C, NIST[1])**	**Water (20°C) (NIST [1])**
Density (kg/m^3)	606	422	998
Surface tension(N/m)	0.0137	0.0129	0.072
Viscosity (Pa/s)	$1.97 * 10^{-4}$	$1.12 * 10^{-4}$	$10 * 10^{-4}$
$Ga^{1/4}$	569	875	441
Ca (mm)	1.52	1.77	2.71

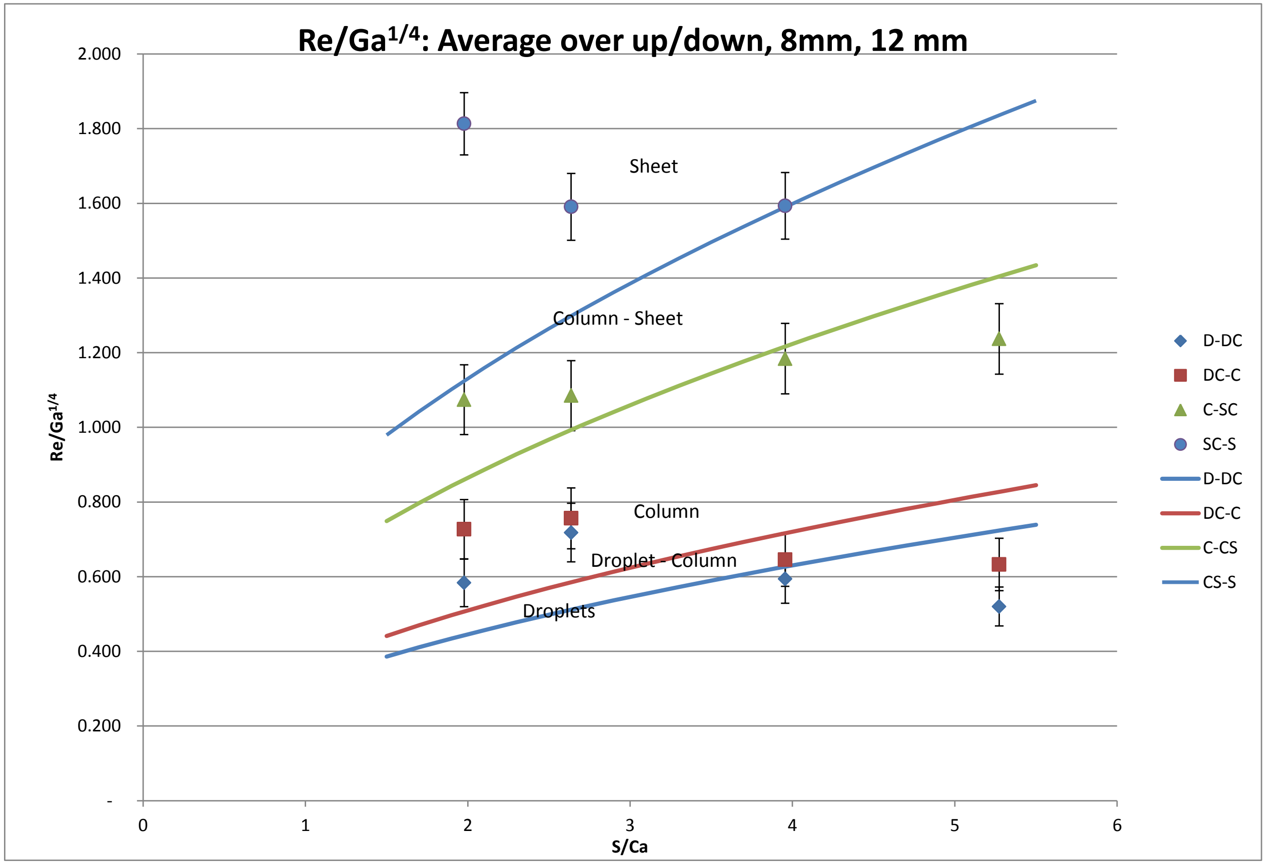
Result Summary, with average for given transition and diameter



- Hysteresis effect evident
- Deviation is 0.14 from model where $Re/Ga^{1/4}$ is constant for given D for a transition

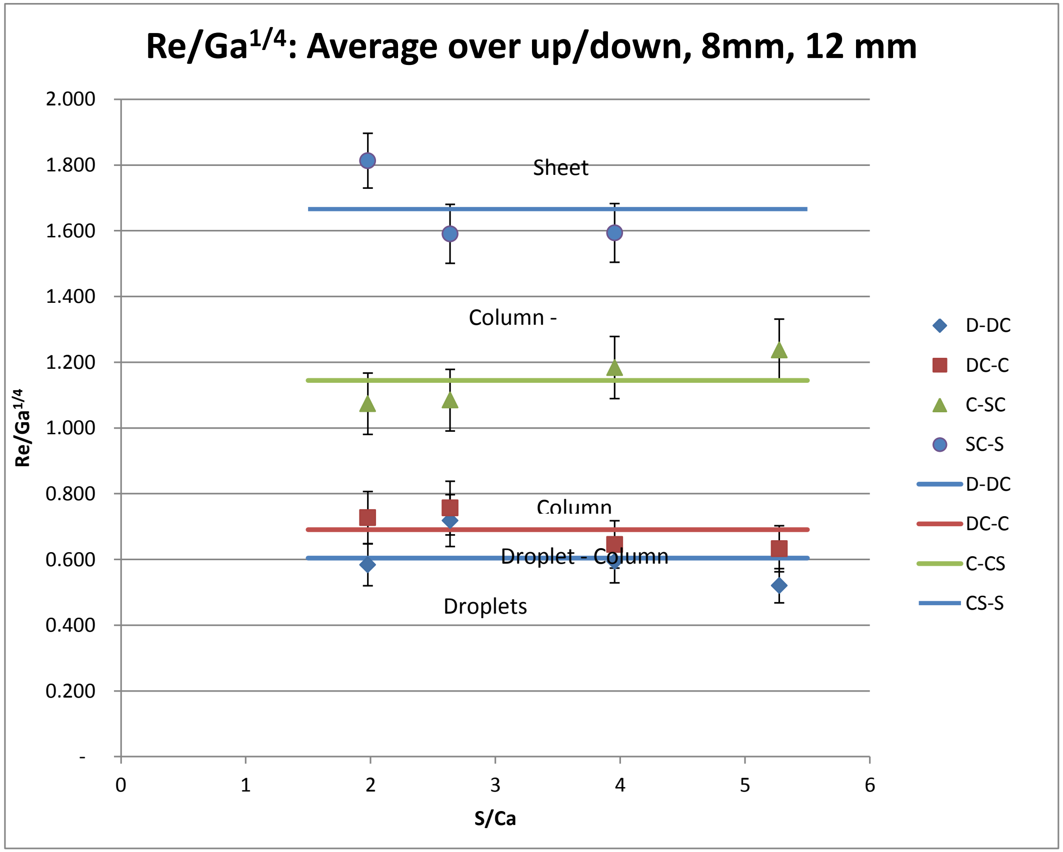
Test of model $Re/Ga^{1/4} = A\sqrt{s/Ca}$

- Results are averaged for tube diameters between 8 and 12 mm
- Results appear invariant of tube separation (s)



Test of model $Re/Ga^{1/4} = A$

- Deviation between model and measurement become here 0.23
  - 0.14 if diameter is separated
  - 0.04 for repeated experiment
- Any dependence between $Re/Ga^{1/4}$ is less than experimental accuracy



Comparison with literature

Uses: $Re = aGa^b$, here to get comparison it is reordered: $\frac{Re}{Ga^{1/4}} = A\left(\frac{Ga}{Ga_{Pentane}}\right)^B$

where $Ga_{Pentane}$= 1.05 *10^{11}.

	This work A, B=0			Honda [2][1] B=0	Armb-uster [3],B=0	Hu & Jacobi [4]		Roques [5]	
	Both	D=8	D=12	A	A	A	B	A	B
Droplet ↔ Droplet – Column	0.61		0.61	0.52	0.20	0.28	0.05	0.30	0.08
Droplet – Column ↔ Column	0.69	0.52	0.94		0.26	0.35	0.05	0.41	0.07
Column ↔ Column – Sheet	1.15	1.02	1.30	1.28	0.94	0.92	-0.02	0.82	0.00
Column – Sheet ↔ Sheet	1.67	1.82	1.58	1.04-1.32[2]	1.14	1.02	-0.01	1.25	0.01

[1]: Low finned tubes, the only one with similar fluid as pentane. [2]:B= -0.014

Comparison with literature (2)

- All studies except Honda have run on water or other fluid with high surface tension and viscosity.
- The others generally have longer distance between the tubes

Conclusions

- The transitions between droplet, column, and sheet flow for pentane have been studied
- The transitions, specially from droplet to column are not easy to identify with pentane due to small surface tension.
- Possibly improved results can be achieved with longer tubes
- In literature, comparable studies have mostly been using fluids with higher surface tension and viscosity and often with longer distances between the tubes.

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