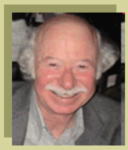
Symposium on
"New Frontiers in Chemical
& Biochemical Engineering"
Thessaloniki, 26-27 Nov. 2009



Effect of Fluid Properties on Flow Pattern in Two-Phase Gas-Liquid Flow in Horizontal & Inclined Pipes

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University of Thessaly, Volos, Greece

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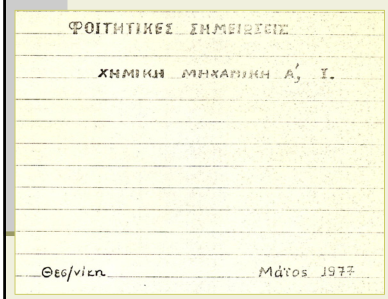
Technological Educational
Institute of Larissa, Greece

Prologue (I)

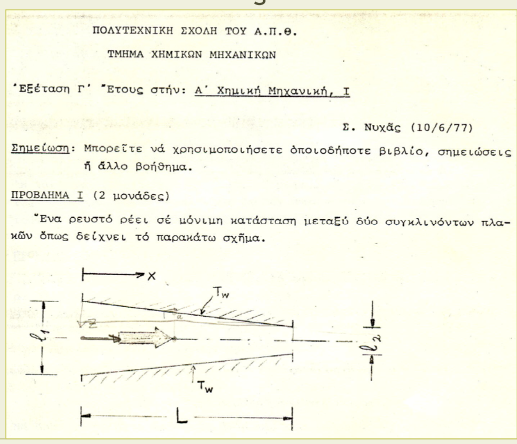
- The course of "Transport Phenomena", first introduced by the young professor ***Stavros Nychas*** in 1976, had a profound influence on my generation of chemical engineers.



ΦΟΙΤΗΤΙΚΕΣ ΣΗΜΕΙΩΣΕΙΣ

ΧΗΜΙΚΗ ΜΗΧΑΝΙΚΗ Α', Ι.

Θεσ/νίκη Μάιος 1977



ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ ΤΟΥ Α.Π.Θ.

ΤΜΗΜΑ ΧΗΜΙΚΩΝ ΜΗΧΑΝΙΚΩΝ

'Εξέταση Γ' 'Ετους στήν: Α' Χημική Μηχανική, Ι

Σ. Νυχᾶς (10/6/77)

Σημείωση: Μπορεῖτε νά χρησιμοποιήσετε ὁποιοδήποτε βιβλίο, σημειώσεις ἤ ἄλλο βοήθημα.

ΠΡΟΒΛΗΜΑ Ι (2 μονάδες)

'Ενα ρευστό ρέει σέ μόνιμη κατάσταση μεταξύ δύο συγκλινόντων πλακῶν ὅπως δείχνει τό παρακάτω σχῆμα.

Prologue (II)

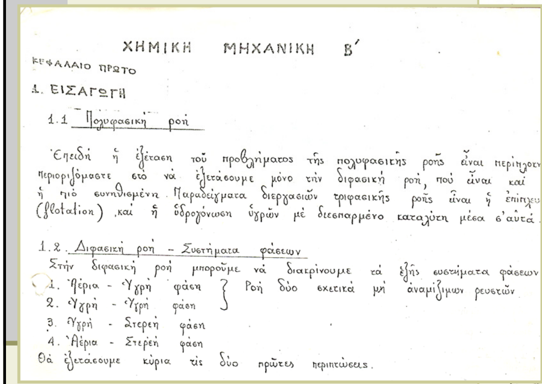
- This paper is connected in many ways to our **teacher**, colleague and friend ***Prof. Tassos Karabelas.***
- Three of the co-authors have graduated from the Chemical Engineering Department at AUTh, having carried out their Diploma Thesis under the supervision of **Tassos Karabelas.**
- Three of us have collaborated with Tassos' PhD advisor, **Prof. Tom Hanratty**.
- Two of us have worked for many years at the ***Laboratory of Natural Resources and Alternative Energy Sources*** **of CPERI-CERTH**, under the direction of Tassos Karabelas.

Prologue (III)

- Prof. Tassos Karabelas joined the Department of Chemical Engineering at AUTh in the summer of 1978 (*just after the earthquake* ?).
- Then I was in the final year of my studies and he introduced us two new courses:
  a) The first was called **"Industrial Plant Design"**, accompanied by the well known "thema" of chemical engineers (with too many sleepless nights in order to pursue the work), that made Tassos famous to the industrial community in Greece.

  b) The second course was a "surprise" one. As he explained to us, he was assigned to teach "Chemical Engineering B", but instead he taught ***"Multiphase Systems".***

Prologue (IV)


ΧΗΜΙΚΗ ΜΗΧΑΝΙΚΗ Β΄

ΚΕΦΑΛΑΙΟ ΠΡΩΤΟ

1. ΕΙΣΑΓΩΓΗ

1.1 Πολυφασική ροή

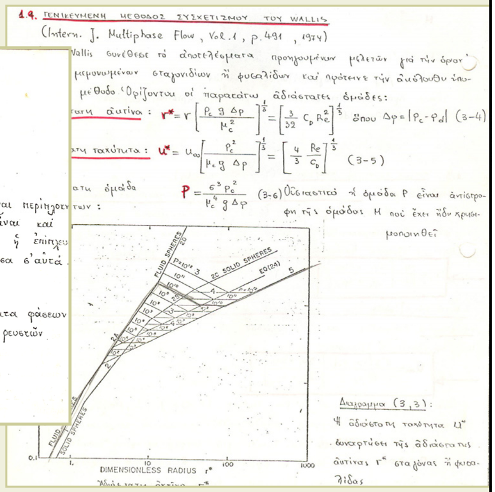
Ἐπειδή ἡ ἐξέταση τοῦ προβλήματος τῆς πολυφασικῆς ροῆς εἶναι περίπλοκη περιοριζόμαστε στό νά ἐξετάσουμε μόνο τήν διφασική ροή, πού εἶναι καί ἡ πιό συνηθισμένη. Παραδείγματα διεργασιῶν τριφασικῆς ροῆς εἶναι ἡ ἐπίπλευ (flotation) καί ἡ ὑδρογόνωση ὑγρῶν μέ διεσπαρμένο καταλύτη μέσα σ'αὐτά.

1.2. Διφασική ροή – Συστήματα φάσεων

Στήν διφασική ροή μπορούμε νά διακρίνουμε τά ἑξῆς συστήματα φάσεων

1. Ἀέρια - Ὑγρή φάση } Ροή δύο σχετικά μή ἀναμίξιμων ρευστῶν
2. Ὑγρή - Ὑγρή φάση }
3. Ὑγρή - Στερεή φάση
4. Ἀέρια - Στερεή φάση

Θά ἐξετάσουμε κύρια τίς δύο πρῶτες περιπτώσεις.



- The state-of-the-art notes (about 80 pages) were handwritten by my colleague Panagiotis Moutzouris and myself and checked by Prof. Karabelas.

Prologue (V)

- I was not the first student to ask Tassos Karabelas for a Diploma Thesis, but I was the first to be examined in a July 1979 morning, along with P. Moutzouris, A. Cangellari and F. Plaka.

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ
ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ
ΤΜΗΜΑ ΧΗΜΙΚΩΝ ΜΗΧΑΝΙΚΩΝ
ΕΔΡΑ: ΤΕΧΝΟΛΟΓΙΑ ΧΗΜΙΚΩΝ ΕΓΚΑΤΑΣΤΑΣΕΩΝ
ΚΑΘΗΓΗΤΗΣ: Α. Ι. ΚΑΡΑΜΠΕΛΑΣ

ΔΙΦΑΣΙΚΗ ΟΜΟΡΡΟΗ ΜΕΣΩ ΣΤΗΛΩΝ ΜΕ ΠΛΗΡΩΤΙΚΑ ΥΛΙΚΑ
(ΔΙΑΒΡΕΧΟΜΕΝΕΣ ΚΛΙΝΕΣ - TRICKLE BEDS)
ΑΡΧΕΣ ΣΧΕΔΙΑΣΜΟΥ

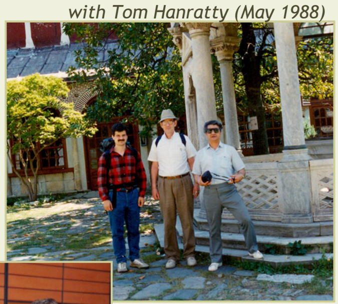
ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ
ΤΟΥ ΦΟΙΤΗΤΗ
ΝΙΚΟΛΑΟΥ ΑΝΔΡΙΤΣΟΥ

ΘΕΣΣΑΛΟΝΙΚΗ 1979

Prologue (VI)

Laboratory (1988)

At Vatopedi Monastery, Mount Athos, with Tom Hanratty (May 1988)



With T.J. Hanratty at the 3rd International Conference on Multiphase Flow, Lyon (June 1998)

Prologue (VII)- *Academic Tree of Tassos Karabelas*

A.J. Karabelas
Univ. Illinois, 1970

T.J. Hanratty
Princeton Univ., 1953

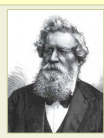
R.H. Wilhelm
Columbia Univ., 1937

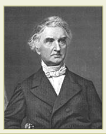
R.H. McKee
Univ. Chicago, 1901

J. O. Stieglitz
Berlin Univ., 1889

J.C.W.F. Tiemann
Univ. Berlin., 1870

A.W. von Hoffmann
Giesen Univ., 1841





J. von Liebig
Univ. Erlangen, 1822

K.F.W.G. Kastner
Univ. Jena, 1805

Nicolo da Lonigo
Univ. Pudua 1453 (MD)

J.L. Gay-Lussac
MA, Univ. Paris, 1800

From V.V. Mainz & G.S. Girolami, Urbana, 1988 (www.scs.uiuc.edu/~mainzv/Web_Genealogy)

Prologue (VIII)

- And finally, with Tassos as head of the *Laboratory of Natural Resources and Alternative Energy Sources* there was not a chance to get bored:
  - *Multiphase Flow*
  - *Geothermal Energy*
  - *Scaling in heat exchangers*
  - *CdS deposition*
  - *Particulate deposition*
  - *Membrane processes*
  - *Water treatment*
  - ....

- And now our contribution in brief.

Introduction

- The knowledge of the flow pattern prevailing in a pipe is crucial in the prediction of flow characteristics (e.g. *pressure drop, liquid holdup, interfacial mass and heat transfer*) in two-phase gas-liquid flow.

- The formation of a specific flow pattern depends upon:
  - flow rates
  - physical properties
  - geometrical characteristics of the pipe *(shape, equivalent diameter, inclination angle etc).*

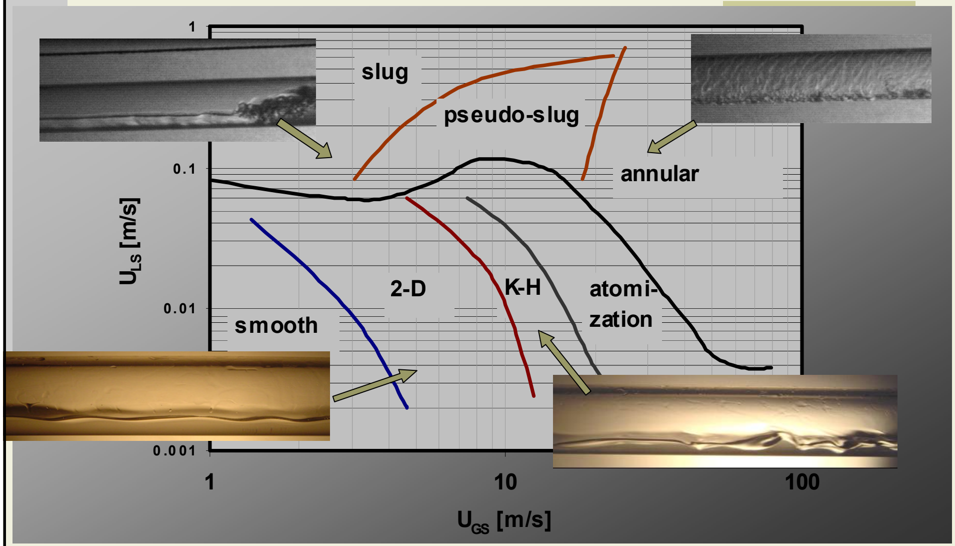
Introduction

The following flow regimes can be recognized in horizontal and near-horizontal two-phase gas-liquid flow:

Stratified:
- Stratified smooth
- Two-dimensional (2-D) regular waves
- Kelvin-Helmholtz (K-H) waves (or roll waves)
- Atomization

- Annular flow
- Slug flow (or intermittent)
- Pseudo-slug (or wavy-annular)

Flow regime map



Experimental flow map for air-water system in a 24-mm horizontal pipe

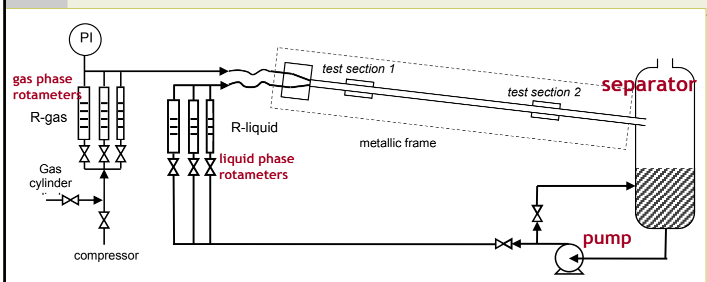
Introduction

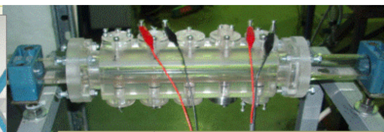
- The effect of fluid properties: studied by a number of researchers over the past 50 years
- Most systematically examined : *liquid viscosity*
- Ambiguity on the effect of *surface tension*: suppresses or enhances interface disturbances? Effect of surface active agents?
- *Inclination angle* significantly affects flow patterns and, consequently, liquid holdup and pressure drop.

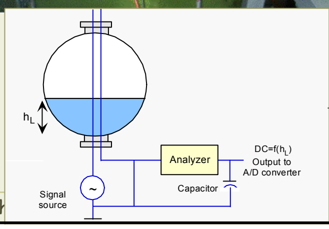
Scope of the Study

- The study aims at elucidating the effect of gas density and surface tension on flow pattern transitions in horizontal and near-horizontal pipes.
- Gas density: air, CO_2 and He
- Surface tension: water, aqueous solution of normal butanol (σ=35 mN/m). Tentative experiments with solution of isopropanol

Experimental Facility and Techniques



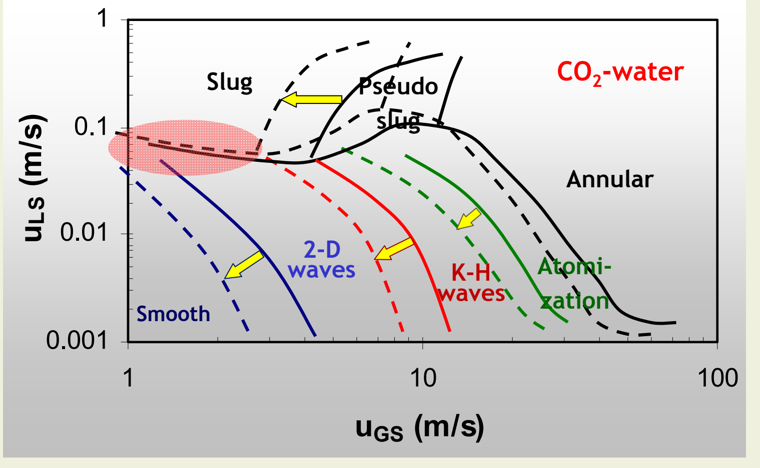




L=13 m, d=24 mm
- Air-Water
- CO_2-Water
- He-Water
- Aqueous sol. butanol-Air

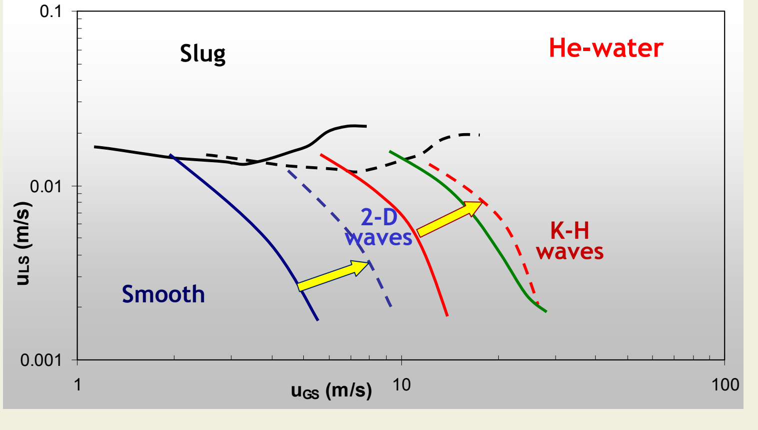
φ=0, ±0.25°, ±0.5° και ±1°

Gas density effect - Horizontal pipe



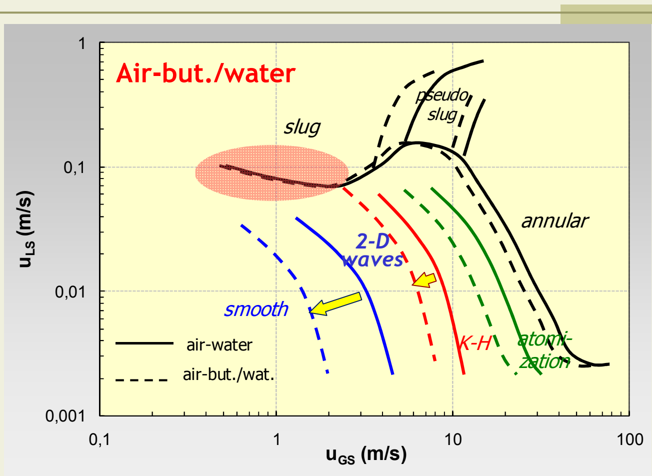
Comparison between air-water (continuous lines) and CO_2-water (dashed lines) flow maps

Gas density effect - Horizontal pipe



Comparison between air-water (continuous lines) and He-water (dashed lines) flow maps

Surface Tension effect - Horizontal pipe



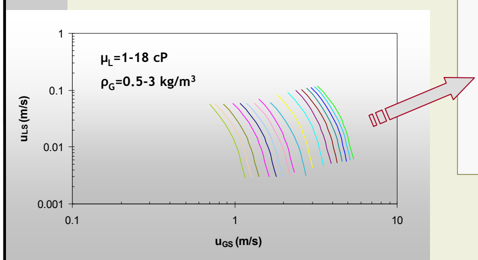
Comparison between air-water (continuous lines) and air-butanol/water (dashed lines) flow maps

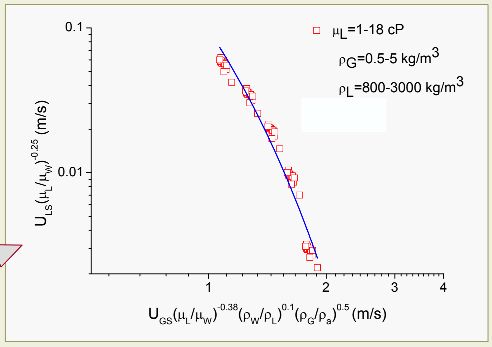
Transition to 2-D wave region

- **Need for a single correlation to use in modelling stratified flow**
- **Taitel and Dukler (1976), on the basis of Jeffrey's sheltering hypothesis, suggested**

$$U_G \ge \sqrt{\frac{4\nu_L\left(\rho_L-\rho_G\right)g}{s\rho_G u_L}}$$

s=sheltering coefficient

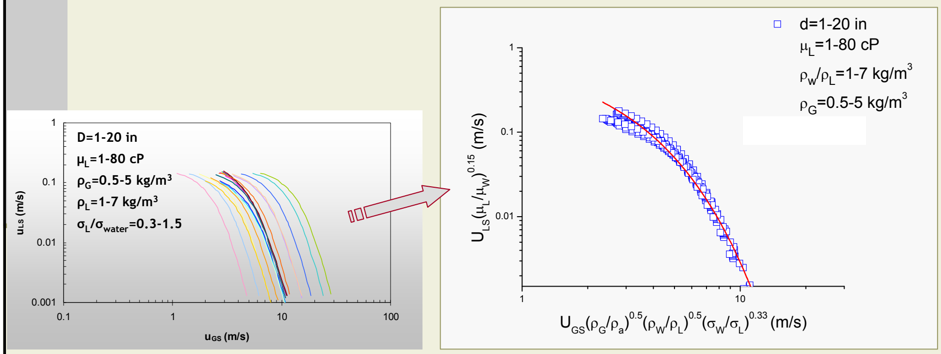




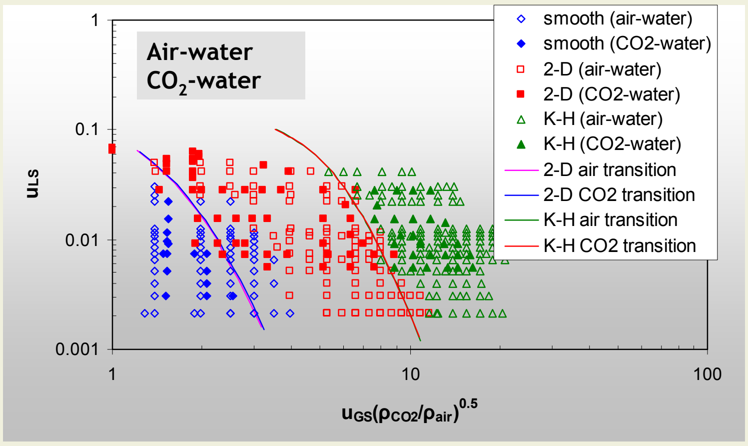
Need to take into account the effect of surface section, $(\sigma_W/\sigma_L)^n$, and to correct for deviations at low h/d (a consequence of Jeffreys's assumptions).

Transition to K-H wave region

- **Modification of the theoretical approach of Lin and Hanratty (1986),** taking into account that when the sheltering mechanism is absent (e.g. high μ_L), small-amplitude disturbances precede the K-H waves.
- **Theory: $u_{GS\text{-}KH} \sim (\rho_G)^{-0.5}$, roughly independent of pipe diameter**

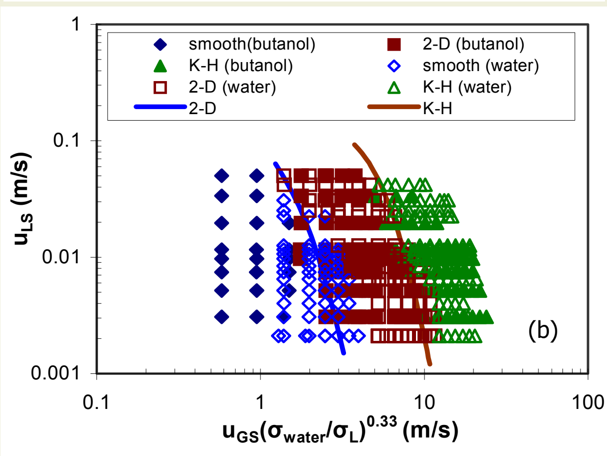


Gas density effect - Horizontal pipe



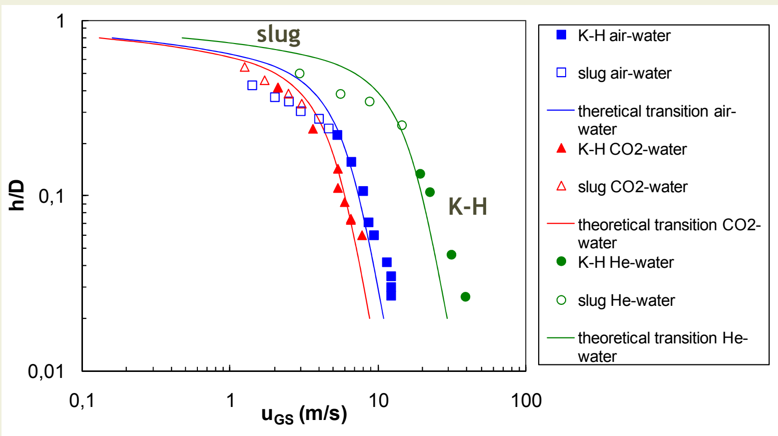
Data on the transition to 2-D and K-H wave patterns in a map with modified coordinate.

Surface Tension effect - Horizontal pipe



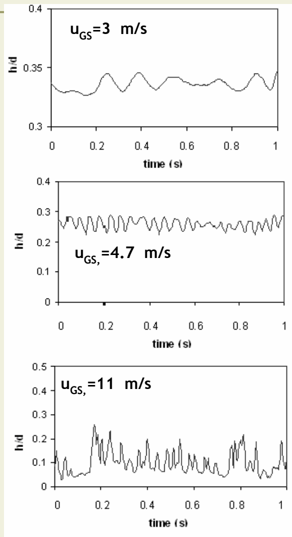
Data on the transition to 2-D and K-H wave patterns in a map with modified coordinate.

Transition to Slug Flow or K-H waves

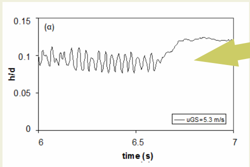


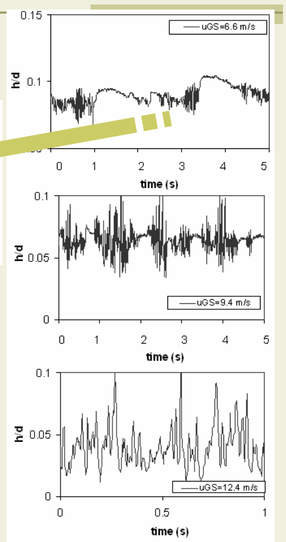
Comparison between experimental transition to slug flow and K-H waves with predictions from the modified Lin-Hanratty model.

Wave Types



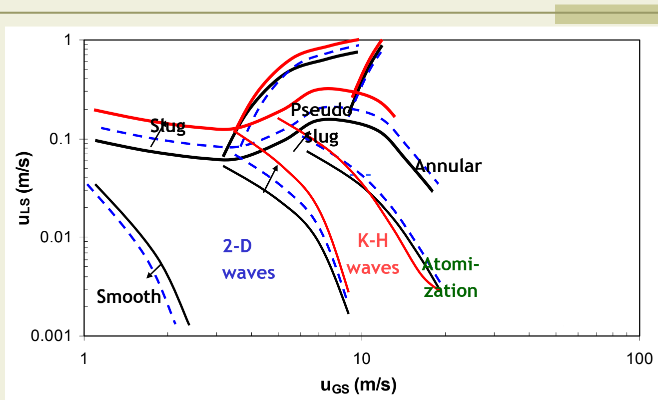
Film height traces for air-water system for u_{LS}=0.042 m/s





Film height traces for butanol-air system for u_{LS}=0.016 m/s

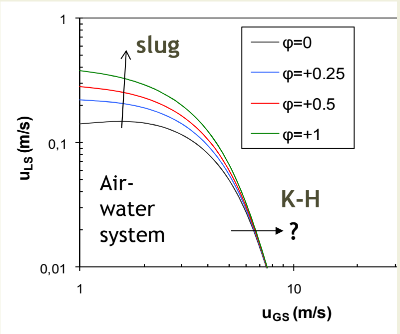
Effect of Downward Inclination



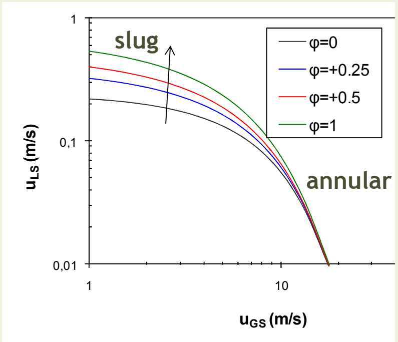
Comparison of CO_2-water flow maps in a horizontal flow (continuous black lines), at φ=0.25° (dashed blue lines) and φ=1° (continuous red lines).

The stratified region is expanded, but the transition to K-H waves is not greatly affected.

Effect of Downward Inclination



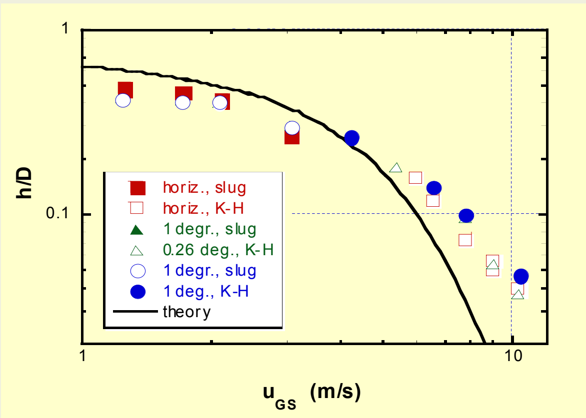
modified Lin-Hanratty model



Taitel-Dukler model

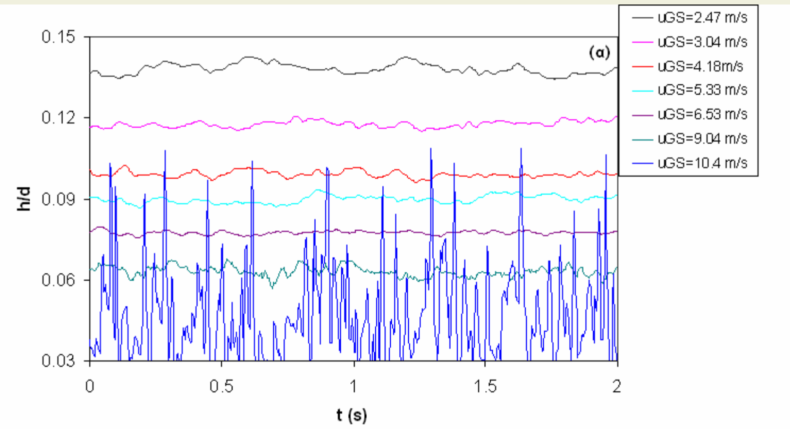
Experiments: increasing gas velocity is required to form K-H waves with increasing inclination angle.

Effect of Downward Inclination



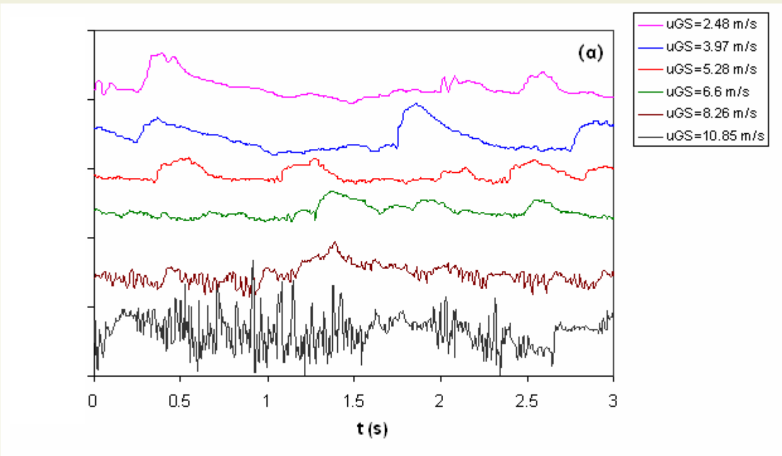
Comparison between experimental film heights at the transition to slug flow and to K-H waves with the modified Lin-Hanratty model (CO_2-water system)

Effect of Downward Inclination-Wave Types



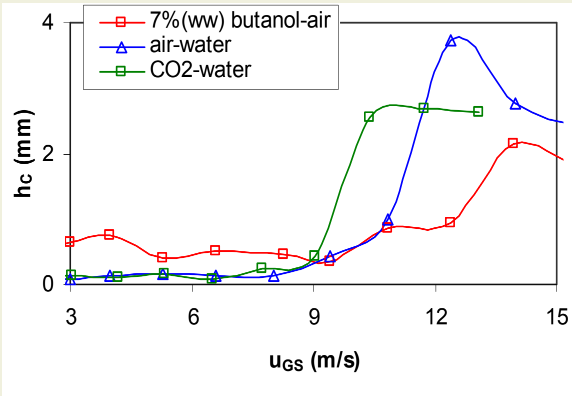
Film height traces in a CO_2-water system for u_{LS}=0.0116 m/s and φ=1°.

Effect of Downward Inclination-Wave Types



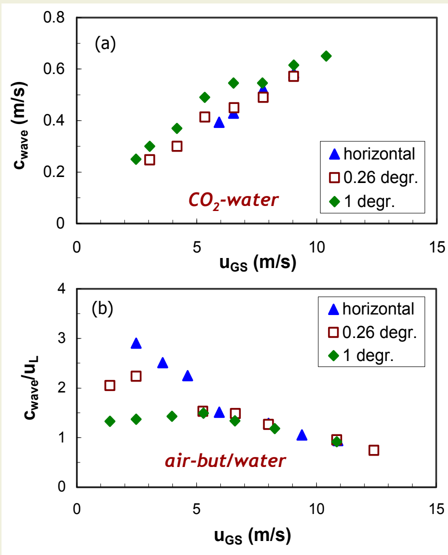
Film height traces in a butanol/water-air system at an angle of 1° (u_{LS}=0.116 m/s).

Effect of Downward Inclination-Wave Characteristics



Wave amplitude with increasing superficial gas velocity at $\varphi=1^o$ (u_{LS}=0.0116 m/s).

Effect of Downward Inclination-Wave Characteristics



Wave velocity as a function of gas velocity and inclination angle for (a) CO_2-water system (u_{LS}=0.0116 m/s).

Relative wave velocity as a function of gas velocity and inclination angle for n-butanol/water-air system (u_{LS}=0.0116 m/s).

Concluding Remarks - *Horizontal Flow*

- A gas density increase and a surface tension decrease shift the transitions to 2-D & K-H waves to lower gas velocities (as predicted by modified models).
- Decrease in surface tension affect more intensely the transition to 2-D waves.
- The transition to slug flow appears unaffected by change of gas density and surface tension.
- Surface tension affects 2-D wave characteristics.

Concluding Remarks - *Downflow*

- Two different types of waves can be indentified in stratified region.
- For $\varphi>1^{o}$ stratified smooth region was not observed even for zero superficial gas velocities.
- Changes in ρ_G and σ affect the transition in inclined pipes in a similar manner as in flow in horizontal pipes.

Thank you for your attention !