

# Two-phase flow in parallel channels: instability, mal-distribution and hysteresis

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# Outline

1. Mal-distribution in gas-solid parallel channels
2. Mal-distribution in gas-liquid parallel channels
3. Possible mechanisms
4. Possible mitigation strategies
5. Summary and future work

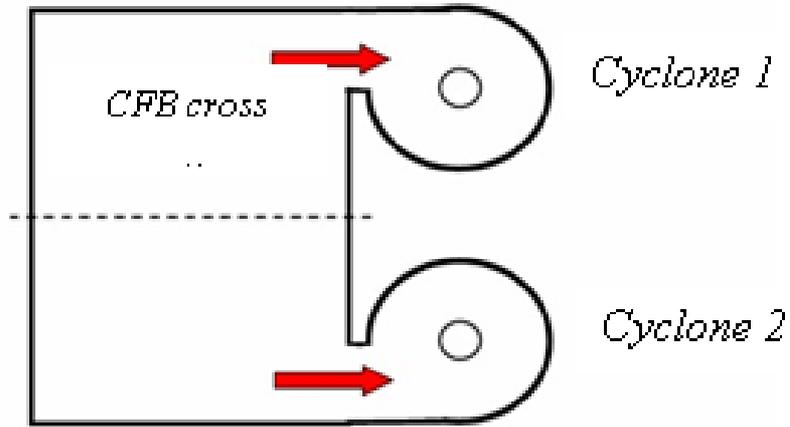


# 1. MAL-DISTRIBUTION IN GAS-SOLIDS PARALLEL FLOW CHANNELS

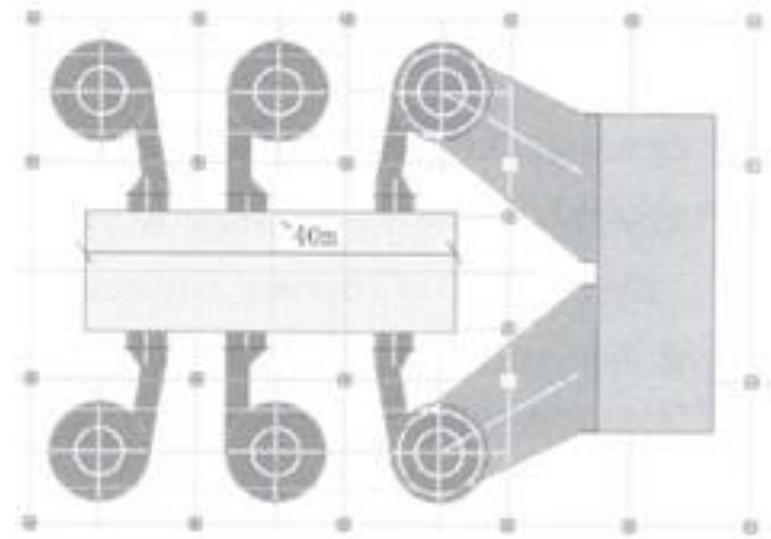


# Mal-distribution in parallel cyclones

1



Masnadi et al. (2010)

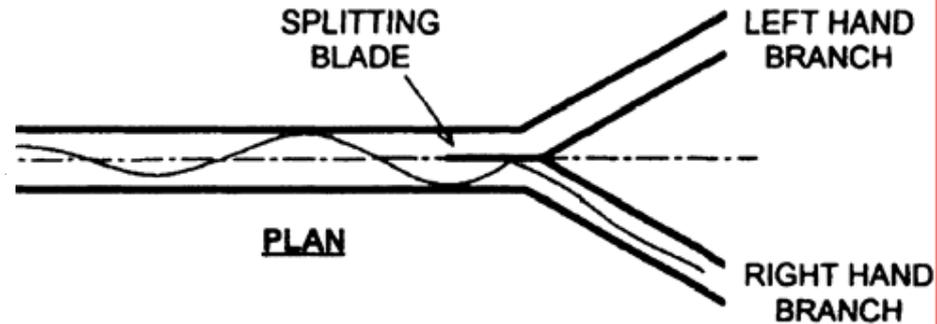
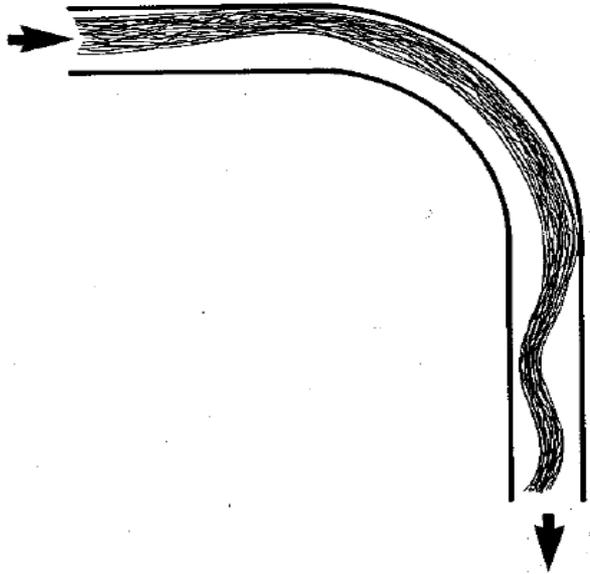


Yue et al. (2008)



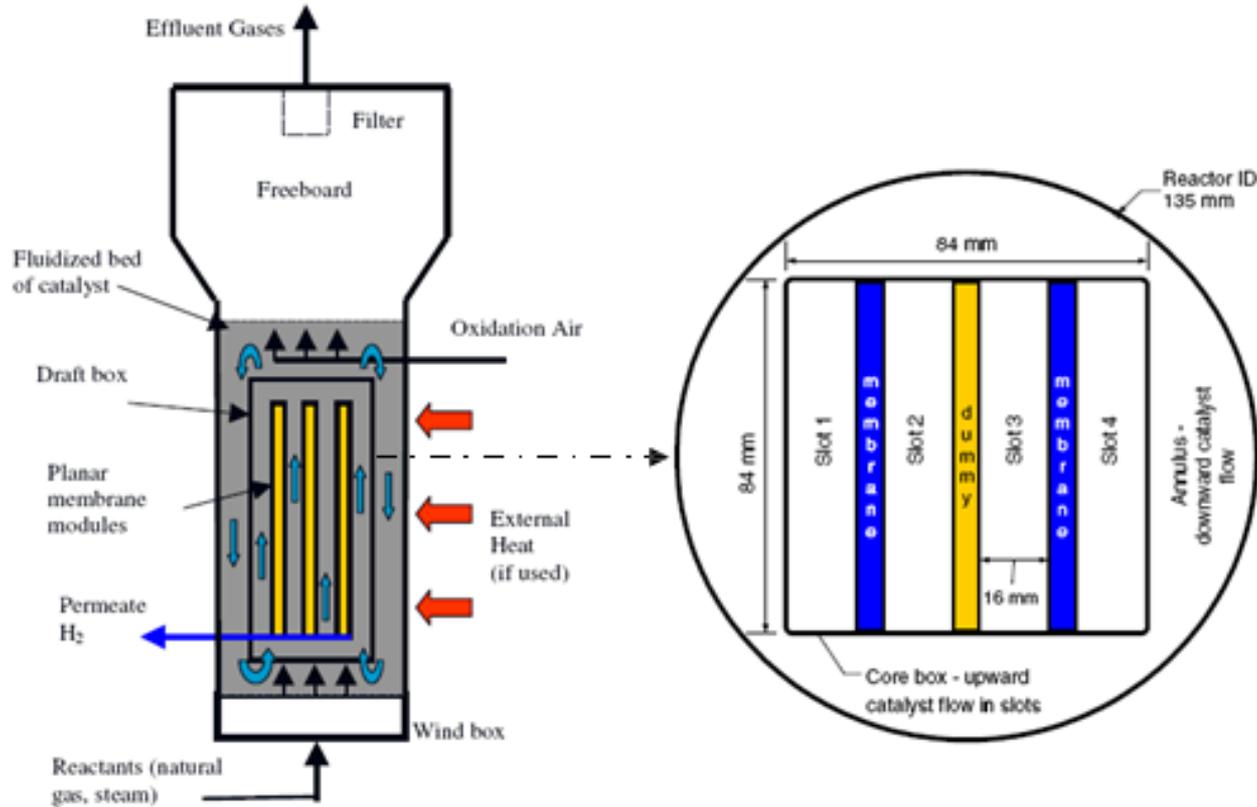


# Mal-distribution in parallel feeding lines



Holmes et al. (2000); Giddings et al. (2004)

# Mal-distribution in slotted membrane fluidized beds



Boyd et al. (2005)

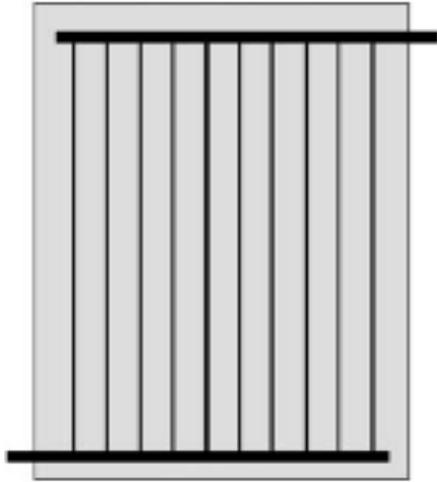
## 2. MAL-DISTRIBUTION IN GAS-LIQUID PARALLEL CHANNELS



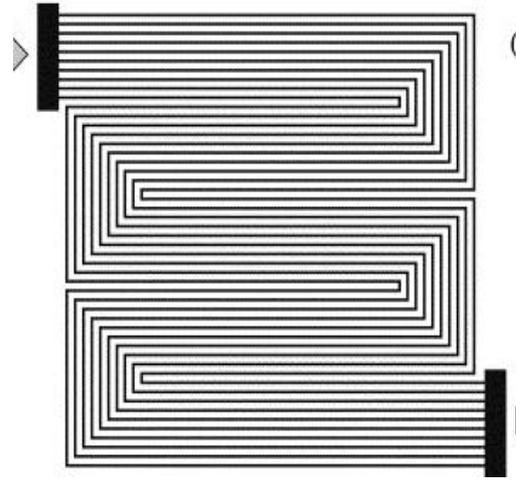


# Gas-liquid parallel flow systems

1. Boiling heat exchangers
2. Water electrolyzer for hydrogen production
3. Fuel cell flow fields



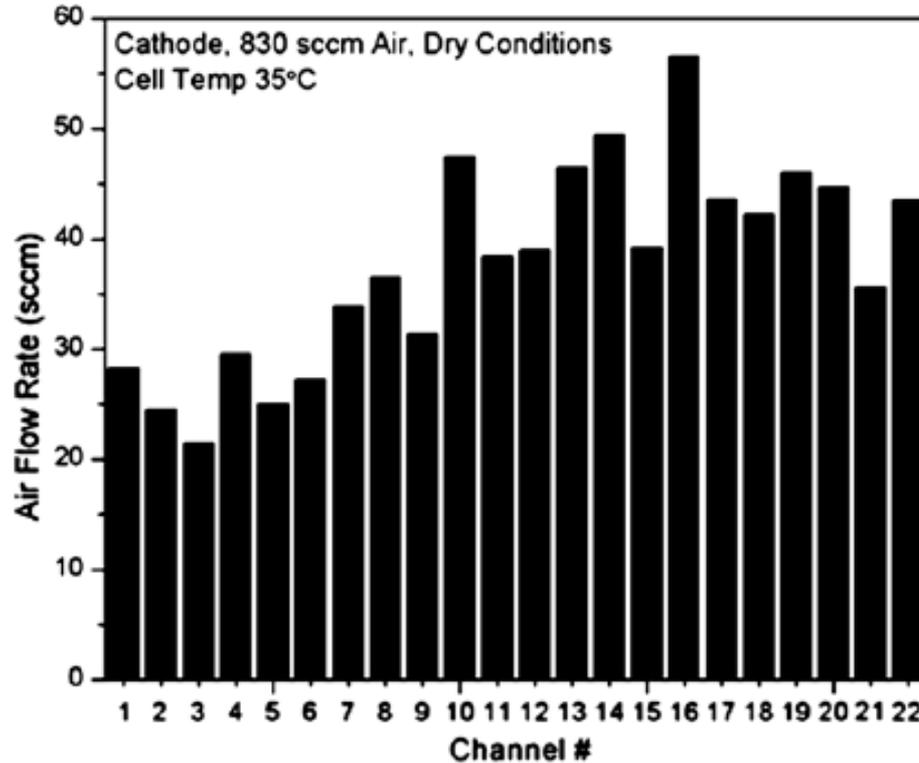
Parallel channels



Serpentine channels

# Maldistribution in multiple parallel channels

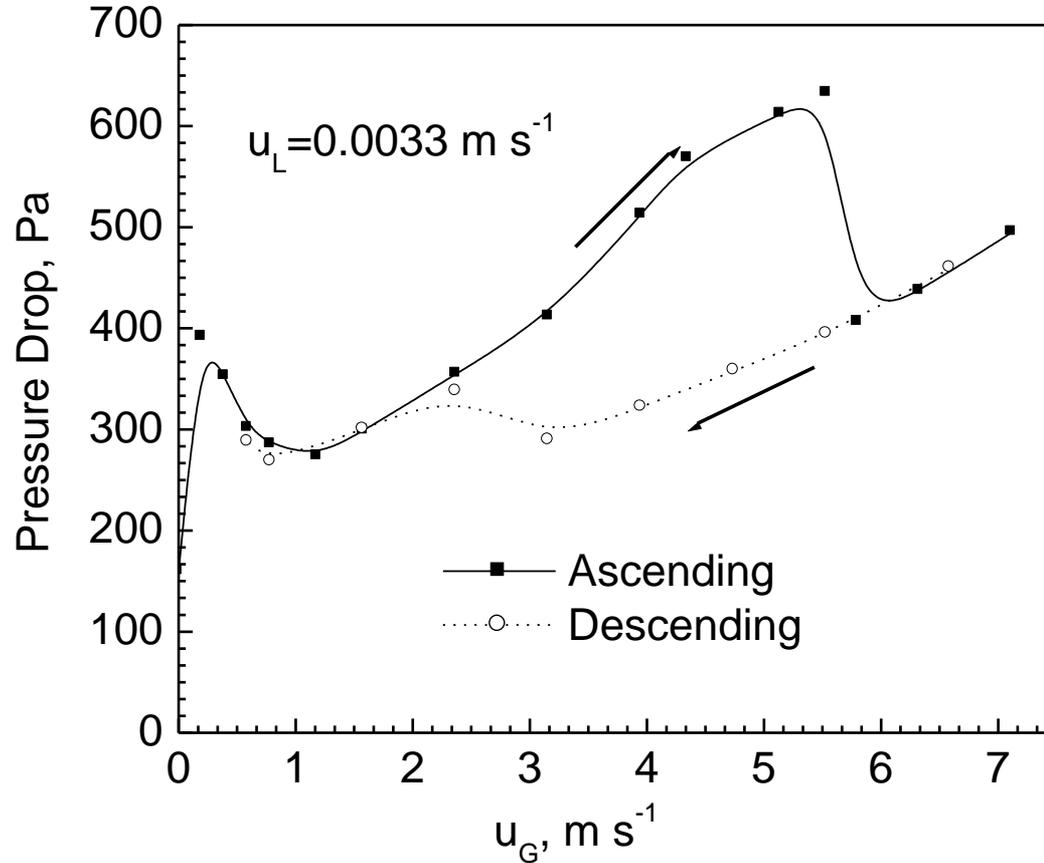
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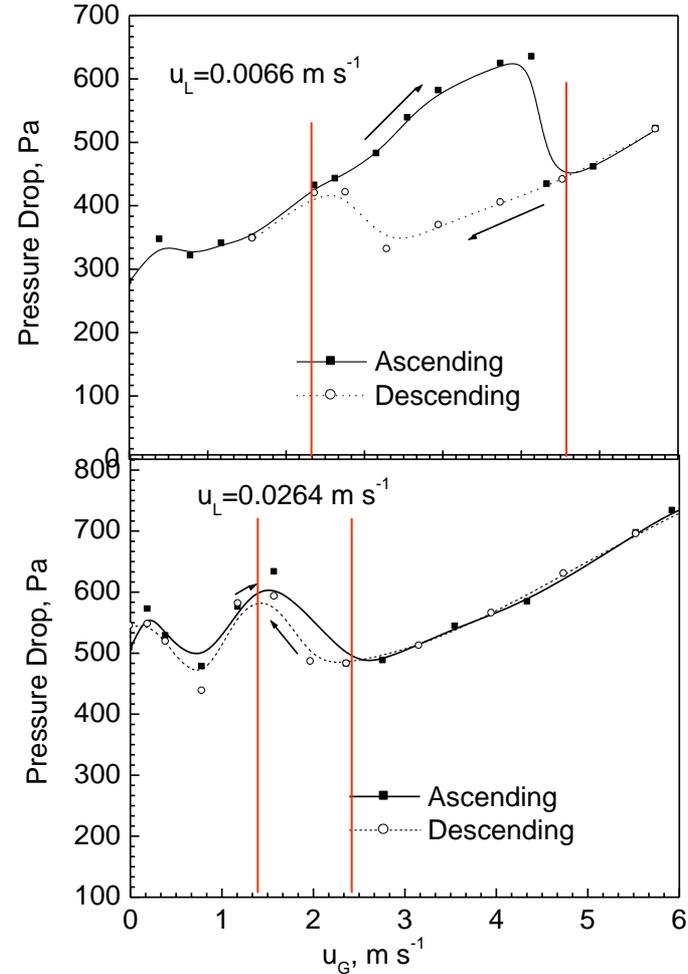
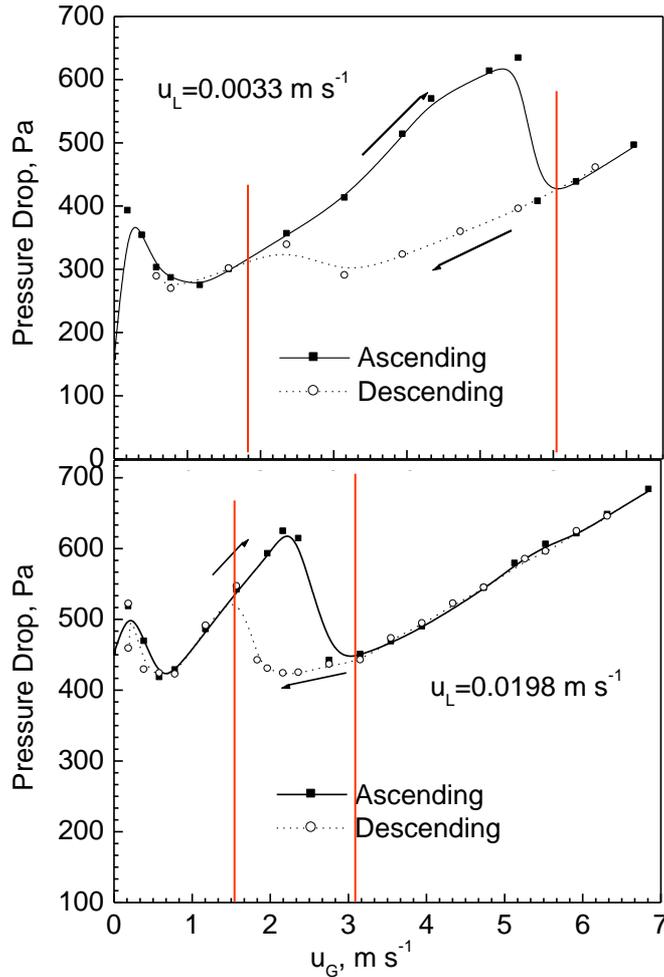
S.G. Kandlikar, et al., *Int. J. Heat Mass Transfer* 52 (2009) 1741-1752.



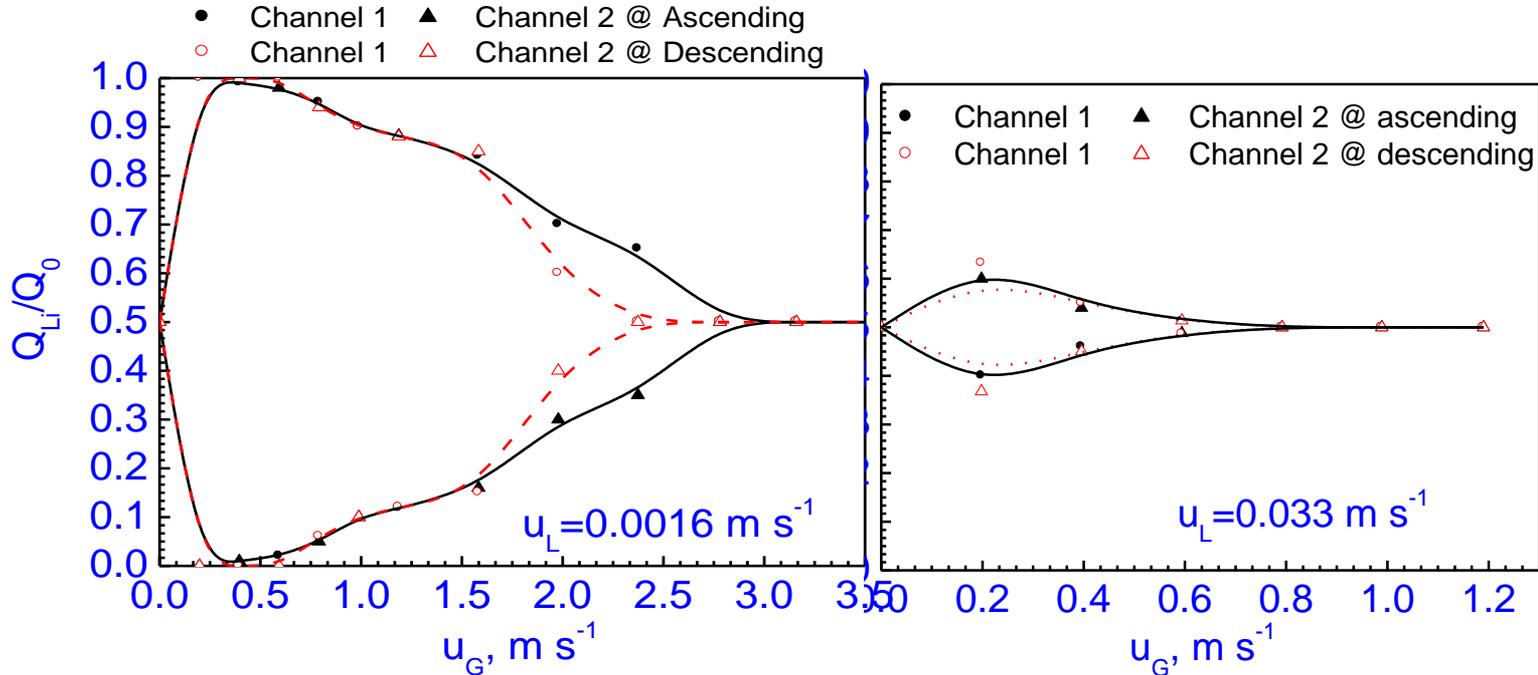
# Flow hysteresis in two identical parallel channels



# Effect of liquid flow rate on hysteresis

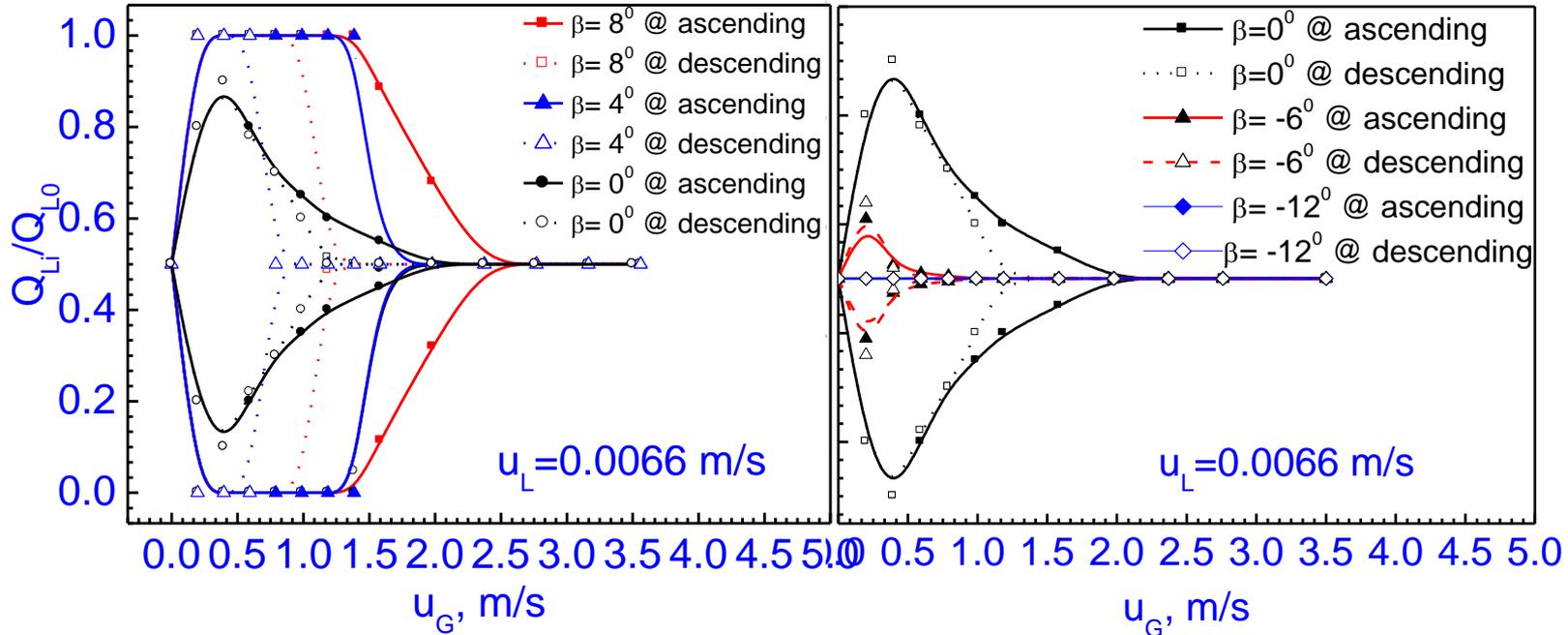


# Effects of liquid flow rates on liquid distribution



*With an increase in the liquid flow rates, flow hysteresis zone decreases and even distribution occurs at a lower gas flow rate.*

## INFLUENCE OF CHANNEL INCLINATION



*Upward inclination enlarges flow hysteresis zone and even distribution requires a higher gas flow rate. In contrast, downward inclination helps in reducing flow hysteresis zone and even distribution occurs at a lower gas flow rate.*

### 3. POSSIBLE MECHANISMS OF FLOW INSTABILITY AND BIFURCATION



## GOVERNING EQUATIONS FOR PARALLEL CHANNEL FLOW

1. Single phase flow in two identical parallel channels:

$$\Delta P = f(U_{g,1}) = f(U_{g,2})$$

$$\text{and } U_{g,1} + U_{g,2} = U_{g,0}$$

$$\text{Therefore, } U_{g,1} = U_{g,2}$$

The flow should be uniformly distributed in the manifold.

2. Two-phase flow in parallel channels:

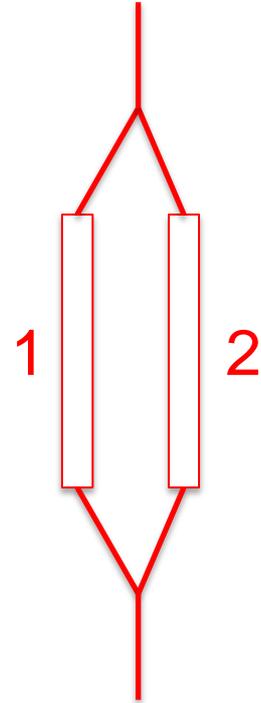
$$\Delta P = f(U_{g,1}, U_{l,1}) = f(U_{g,2}, U_{l,2})$$

$$\text{and } U_{g,1} + U_{g,2} = U_{g,0}$$

$$U_{l,1} + U_{l,2} = U_{l,0}$$

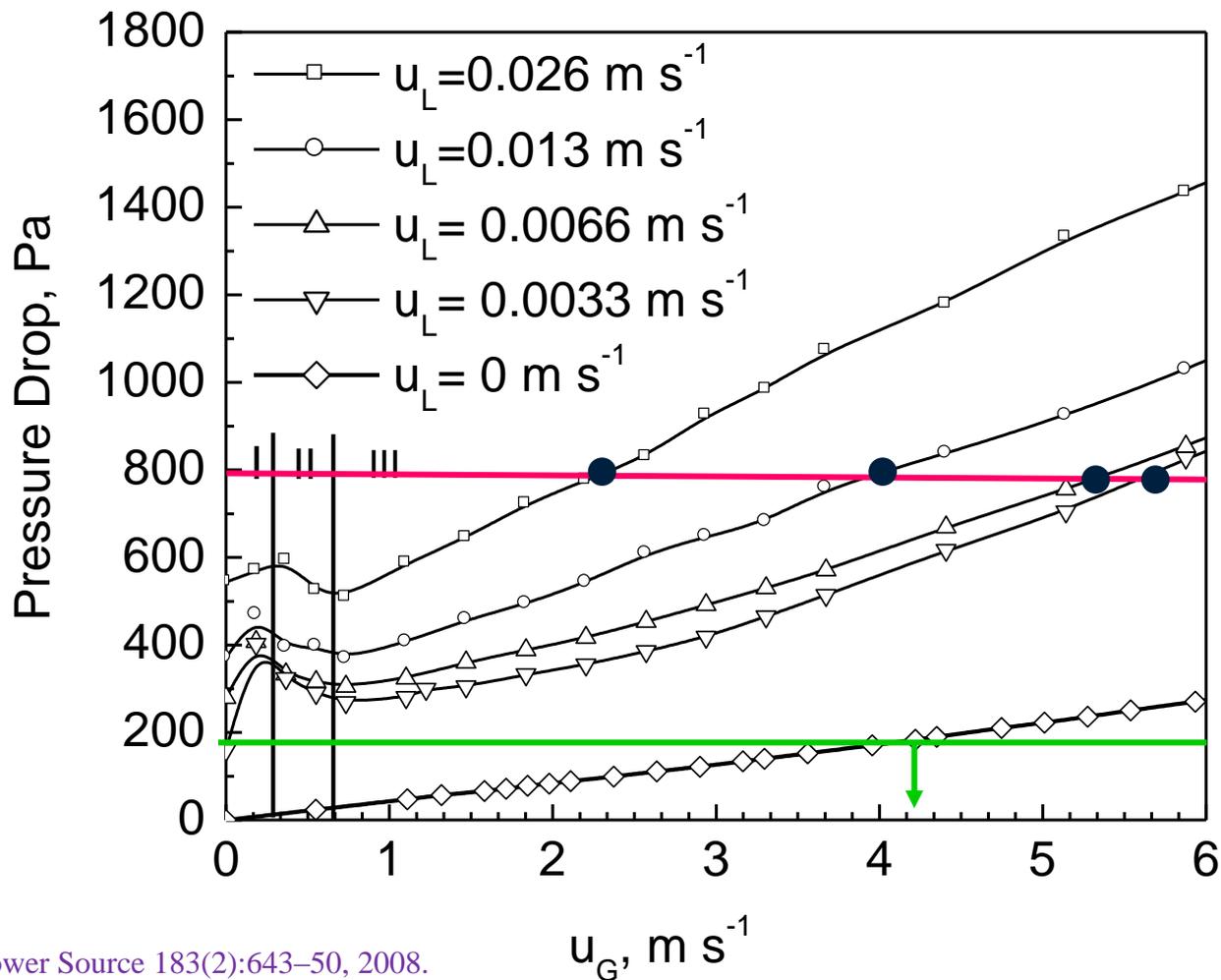
4 variables with 3 equations: Degree of freedom = 1

One more equation or constraint is needed.





# PRESSURE DROP AS A FUNCTION OF GAS AND LIQUID VELOCITIES





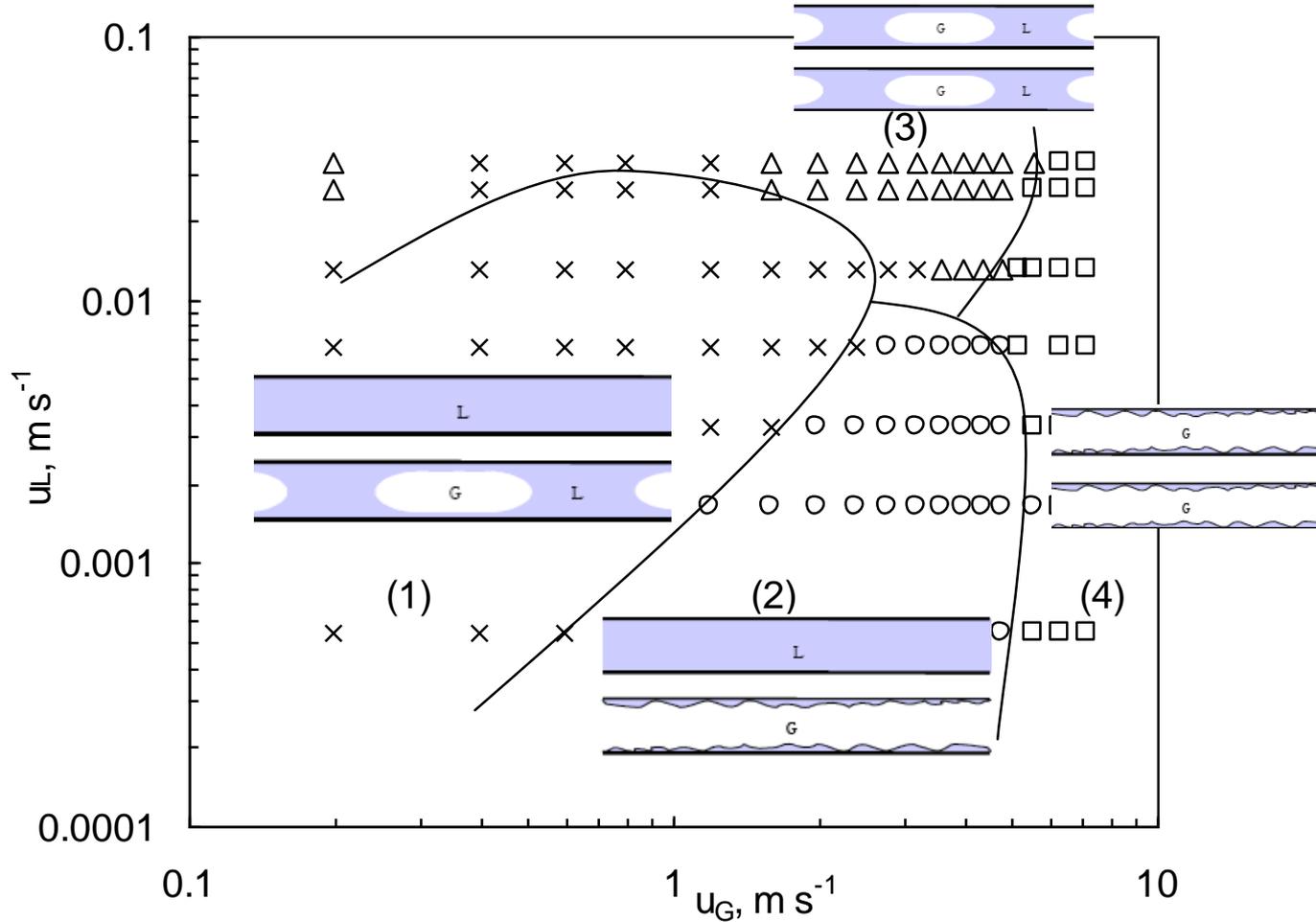
# INSTABILITY AND BIFURCATION CRITERION

1. Energy dissipation minimization (Masnadi et al., 2010; Grace, 2008)
2. Entropy production minimization (Zhang et al., 2016)
3. Energy minimization at multi-scale (EMMS) (Li, 1987).  
Compromise of dominant mechanisms.
4. Perturbation from pressure waves/fluctuations?
5. Perturbation from density waves/fluctuations?

# 3. MITIGATION STRATEGIES



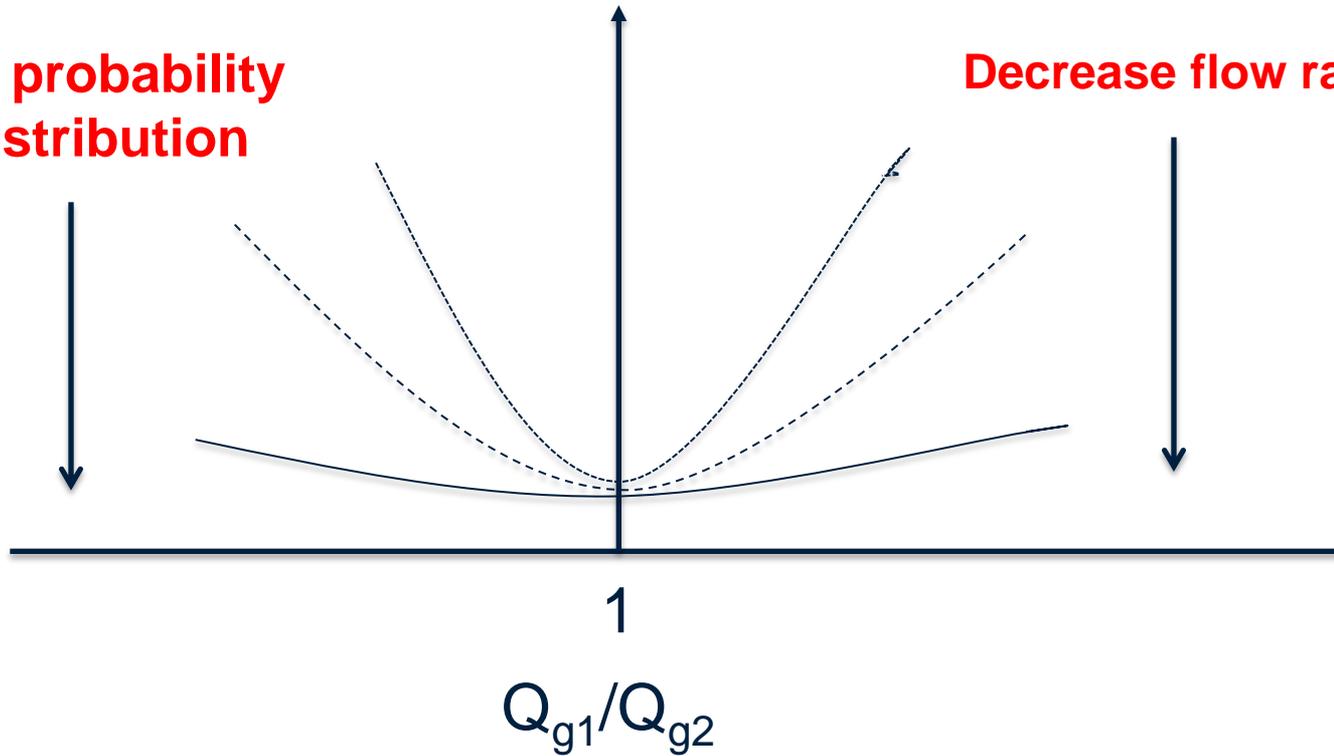
# a. Operate at high flow rates of gas and liquid/solids



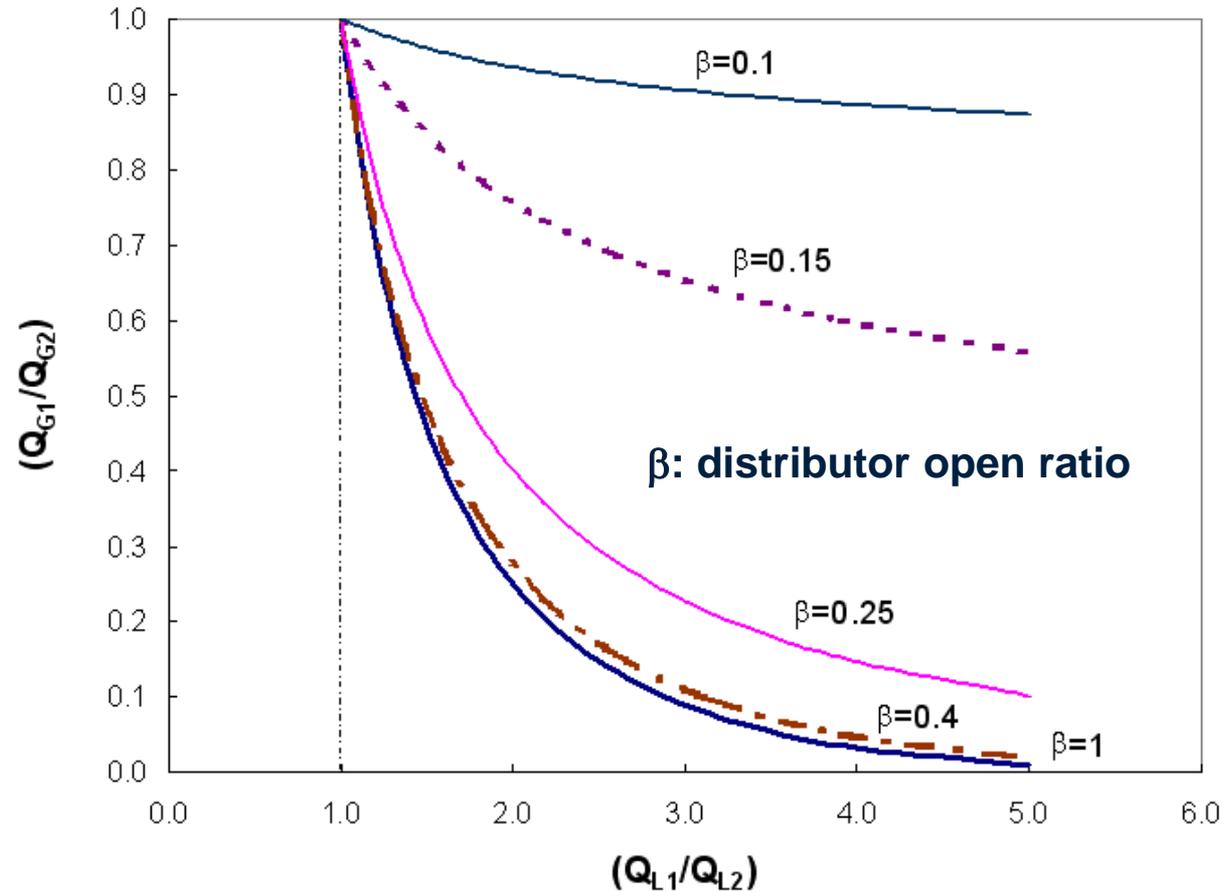
# SENSITIVITY OF PRESSURE DROP TO MAL-DISTRIBUTION

Increase probability  
of mal-distribution

Decrease flow rates



## b. Use inlet distributors for gas distribution



# Preliminary test in an active fuel cell



		Inlet region	Distributor design
R E G	C		
	A		
N F S	C		
	A		

**Inlet distributors can reduce gas mal-distribution**

# Summary and future work



1. Two-phase flow in parallel channels may distribute non-uniformly, still satisfying the identical pressure drop requirement in each channel.
2. There exists flow “hysteresis” for two-phase flow in parallel channels, likely due to the existence of multiple steady states and flow instabilities.
3. The flow mal-distribution is less significant at high gas velocities and high liquid/solids flow rate, and in horizontal or downward inclined channels.
4. Mal-distribution and two-phase flow can be reduced by selecting proper operating conditions and installing inlet distributors.
5. Due to the inherited nature of multiple steady states in two-phase flow in parallel channels, different dominant mechanisms should be identified so that stability criteria can be developed based on the compromise of different control mechanisms such as pressure drop minimization, entropy production minimization, etc.



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# Thank you



a place of mind  
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