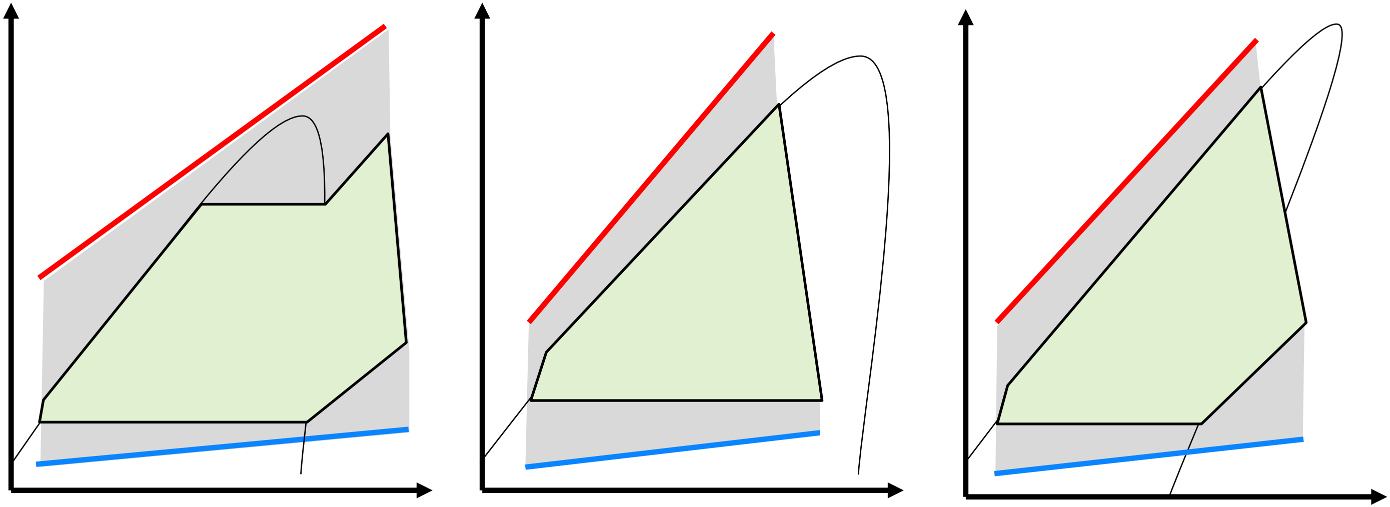
Investigating the validity of the fundamental derivative in the equilibrium and non-equilibrium two-phase expansion of MM

Martin White

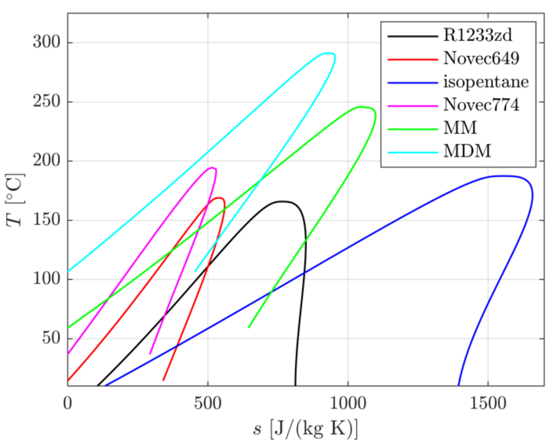
NICFD 2020, 29-30th October 2020

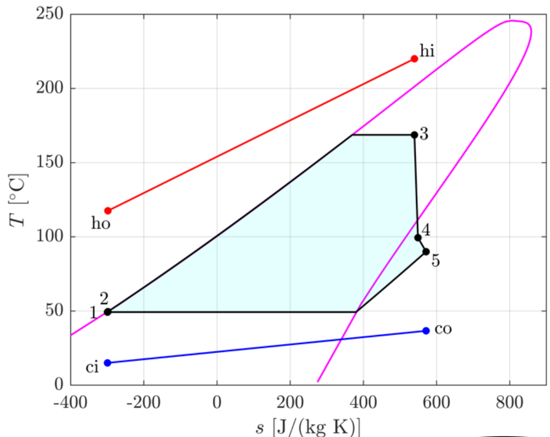
Supported by the UK RAEng through the Research Fellowship funding scheme

The motivation for two-phase expansion



Characteristics of a two-phase ORC turbine





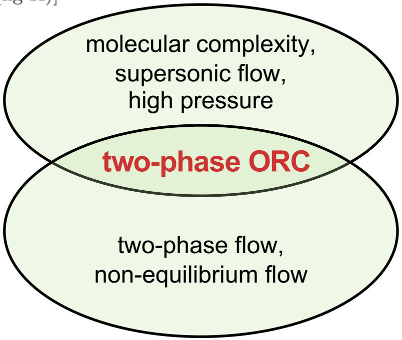
molecularly complex working fluid

low turbine inlet vapour quality

high turbine inlet pressure

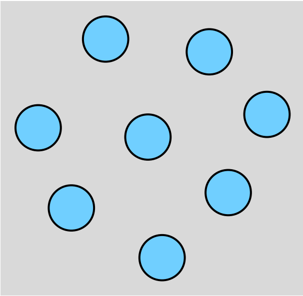
low degree of reaction turbine → high stator expansion ratio

transition for low vapour quality to superheated vapour in stator



Modelling overview

$$\Gamma = 1 + \frac{\rho}{a}\left(\frac{\partial a}{\partial \rho}\right)_s$$



Require a definition for the speed of sound

Speed of sound will depend on:

- thermal interaction between phases
- mechanical interaction between phases

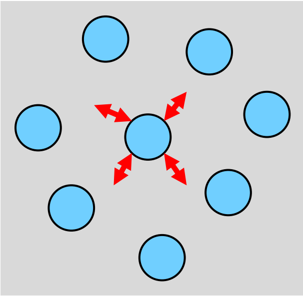
	Momentum equilibrium	**Momentum non-equilibrium**
Thermal equilibrium	$u_L = u_V$ $T_L = T_V$	$u_L \neq u_V$ $T_L = T_V$
Thermal non-equilibrium	$u_L = u_V$ $T_L \neq T_V$	$u_L \neq u_V$ $T_L \neq T_V$

homogeneous flow

Homogeneous modelling

u_V, ρ_V, T_V

u_L, ρ_L, T_L, D



Assumptions:

- well mixed
- very small particle diameter
- negligible surface tension effects

$$p_L = p_V$$
$$u_L = u_V$$

Two extreme cases for heat exchange between phases:

$\rightarrow \infty$ $\quad T_L = T_V = T_{\mathrm{sat}}$ $\longrightarrow$ **thermal equilibrium**

$\rightarrow 0$ $\quad$ insulated $\longrightarrow$ **frozen thermal states**

Homogeneous equilibrium modelling

Speed of sound with phase change (Brennen, 2005):

$$\frac{1}{\rho a^2} = \alpha g_V + (1-\alpha) g_L$$

where:

$$g_i = \frac{1}{\rho_i}\left(\frac{\partial \rho_i}{\partial p}\right)_e - \frac{1}{h_{LV}}\left(\frac{1}{\rho_V} - \frac{1}{\rho_L}\right)\left(1 - \rho_i\left(\frac{\partial h_i}{\partial p}\right)_e\right)$$

α: vapour volume fraction
e: phase derivative
h_{LV}: latent heat of vapourisation

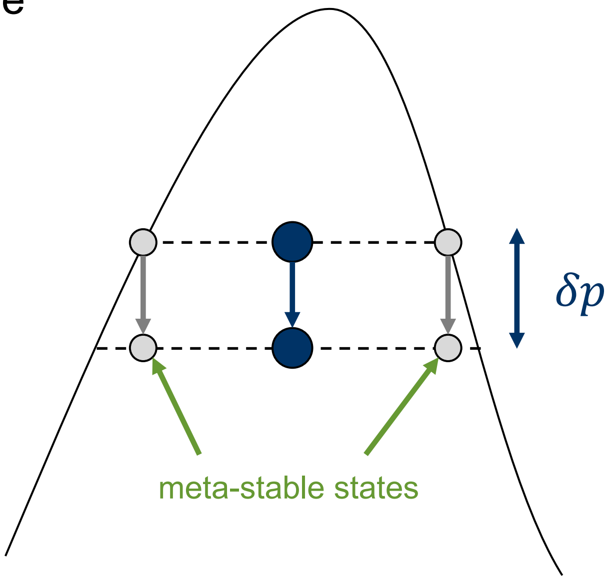
Homogeneous frozen-state modelling

Speed of sound without phase change (Brennen, 2005):

$$\frac{1}{\rho a^2} = \frac{\alpha}{\rho_V a_V^2} + \frac{(1-\alpha)}{\rho_L a_L^2}$$

where:

$$a_i = \sqrt{\left(\frac{\partial p}{\partial \rho_i}\right)_s}$$



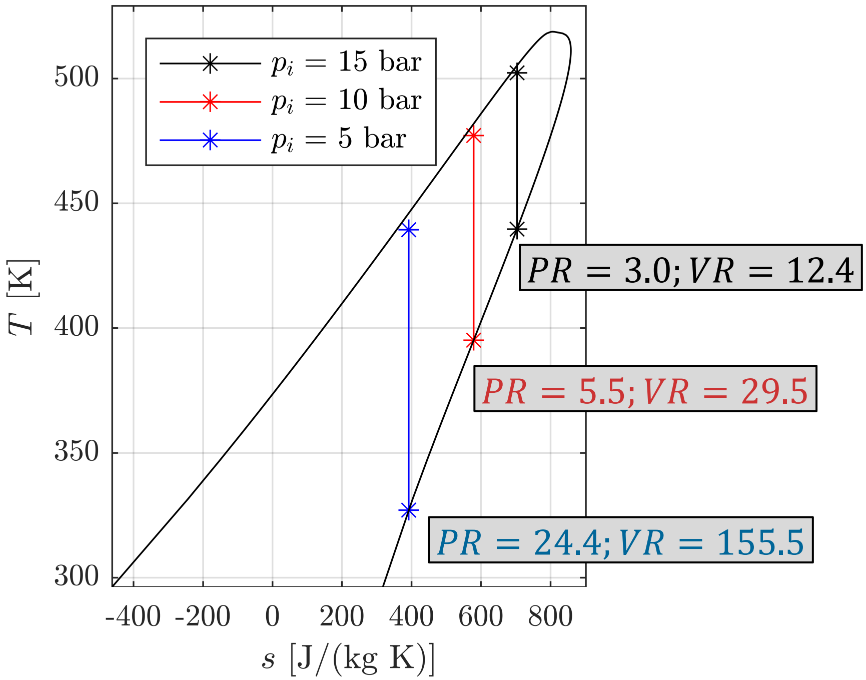
α: vapour volume fraction
s: entropy

Case study

Working fluid:
MM

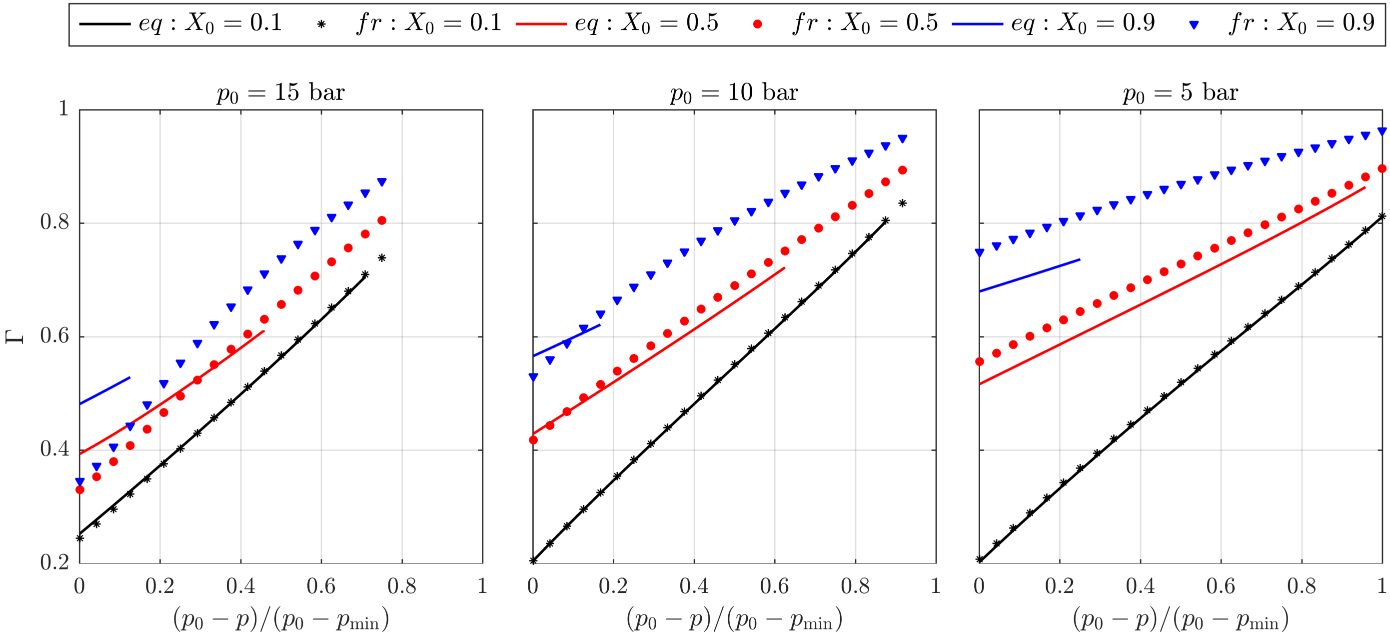
Inlet pressures:
5, 10, 15 bar

Inlet vapour qualities:
0.1, 0.5, 0.9



PR: pressure ratio
VR: volumetric expansion ratio

Fundamental derivative comparison



Conclusions and future works

Two-phase expansion promising candidate for ORC systems

Preliminary investigation of NICFD effects within the two-phase expansion of MM under relevant ORC operating conditions

Expressions for the speed of sound defined and fundamental derivative evaluated for homogeneous thermal equilibrium and frozen thermal states

From reservoir pressures of 5, 10 and 15 bar with reservoir vapour qualities of 0.1, 0.5 and 0.9 expansion remains within a region where $0 < \Gamma < 1$

Deviation in Γ under the frozen state and thermal equilibrium assumptions increased at higher vapour qualities and most significant at high reservoir pressures

Assumption of a homogeneous two-phase mixture is likely an oversimplification, and further investigations are required

Thank you for listening

City, University of London
Northampton Square
London
EC1V 0HB
United Kingdom

T: +44 (0)20 7040 8277
E: martin.white@city.ac.uk
https://www.city.ac.uk/people/academics/martin-white