MACCSOL

SEVENTH FRAMEWORK PROGRAMME

The Development and Verification of a Novel **M**odular **A**ir **C**ooled **C**ondenser for Enhanced Concentrated **Sol**ar Power Generation

ACC Users Group 5th Annual Meeting
October 16th, 2013

"Performance Characteristics of a Novel Modular Air-Cooled Condenser"

Presented by:
Alan O'Donovan (Ph.D. Candidate, University of Limerick)

UNIVERSITY of LIMERICK
OLLSCOIL LUIMNIGH

Presentation Overview

- Project Background
- Objectives
- Current Practice in ACCs
  - Measurements on Conventional A-Frame ACC in Ireland
- Modular ACC (MACC) Design
- Experimental Measurements on MACC Prototype
  - Air-side characterisation
  - Steam-side characterisation
- Impact on Plant Output
- Current Work

MACCSOL

SEVENTH FRAMEWORK PROGRAMME

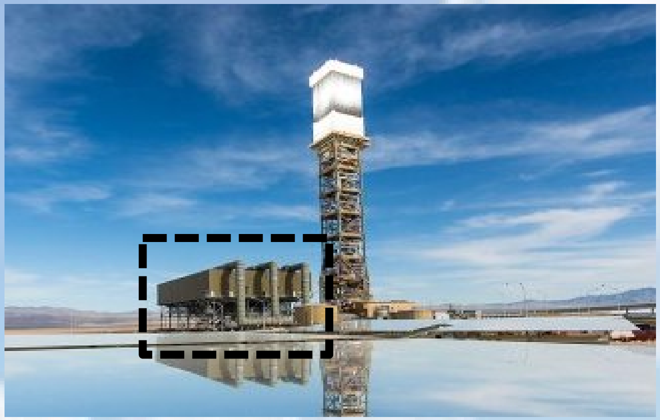
Project Background

- In March 2007 the EU committed to source 20% of Europe's electricity from renewable sources by 2020
  - Concentrated Solar Power (CSP) is forecasted to provide 25% of this target
  - 630,000 TWh/y of solar radiation falls on the Mediterranean region (Europe consumes just 4,000 TWh/y ~0.6% of available energy)


DESERTEC-EUMENA
Concentrating Solar Power
Hydro
Photovoltaics
Biomass
Wind
Geothermal
DESERTEC FOUNDATION
CSP collector areas for electricity
World 2005
EU-25 2005
MENA 2005
TRANS-CSP Mix EUMENA 2050

Project Background

- CSP development is being prioritised by EU
- Barriers to maximising CSP potential
  - Absence of cooling water for condensers in Rankine Cycle
  - Inefficiency of current air-cooling methodologies



- According to the European Strategic Energy Technology (SET) plan a <u>25% loss in CSP plant output</u> can occur on warm days

MACCSol

SEVENTH FRAMEWORK PROGRAMME

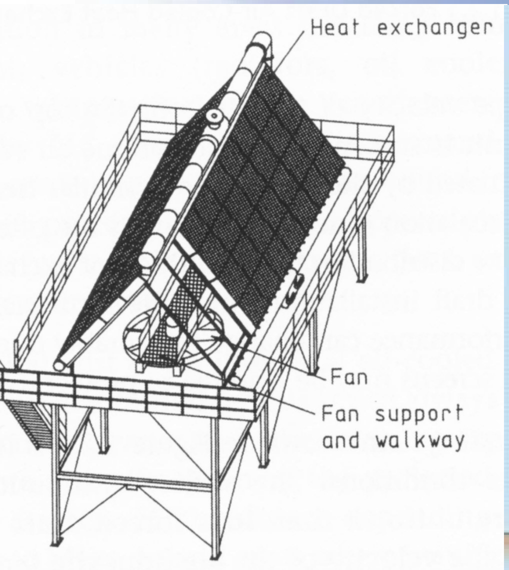
Project Background

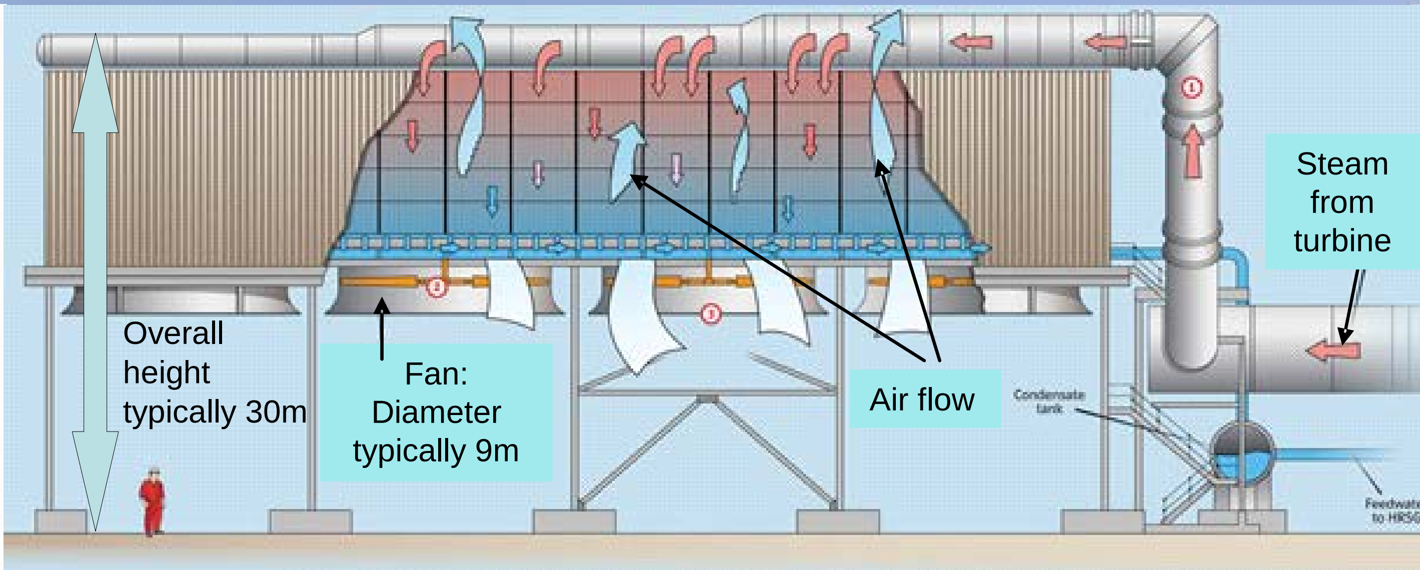
- For successful deployment of CSP, enhanced air-cooling methodologies must be developed
- Seventh EU Framework programme (FP7) provides funding to successful project proposals
- MACCSol secured €7m funding in 2010
  - Consortium consists of 3 universities and 5 industrial partners

Objectives

- High level objectives:
  - Facilitation of EU's 2020 renewable energy target
  - Ensure successful deployment of CSP
  - Elimination of water for cooling CSP condensers
  - Minimise inefficiencies and losses associated with current ACCs
  - Maximise power output from air-cooled CSP plants
  - Ensure CSP is cost-competitive with fossil-fuel based power generation

Current Practice in ACCs





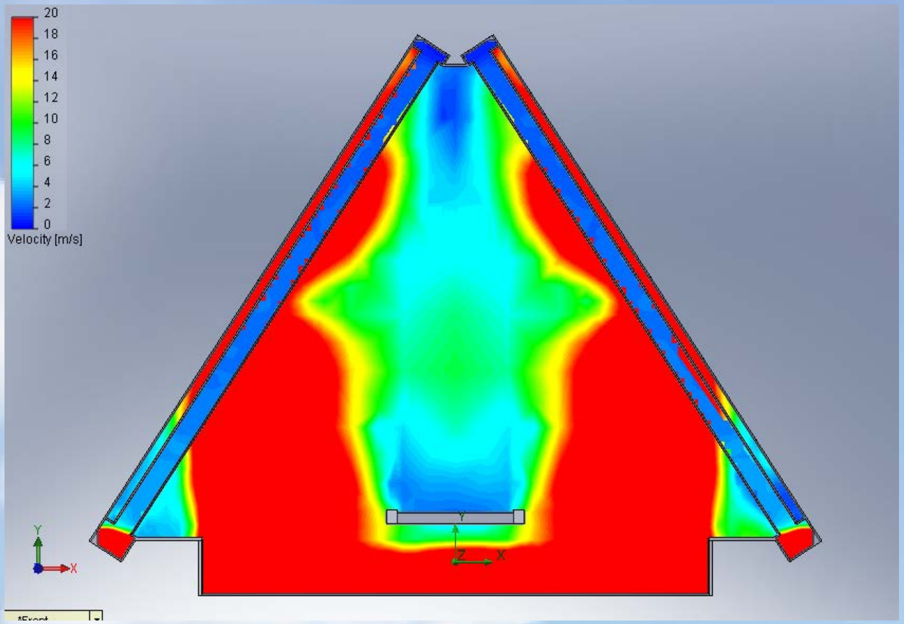
- Large diameter fans are typically two-speed
  - Since the fans are switched in steps, certain deviations upward or downward from the desired set point are unavoidable
- Fans typically consume 150kW
  - 20 fans for 150 MW plant (Irish Power Plant)
  - 20 x 150kW = 3MW = 2% of plant output
- Large structures are costly to erect
  - High strain rates can eventually lead to failure

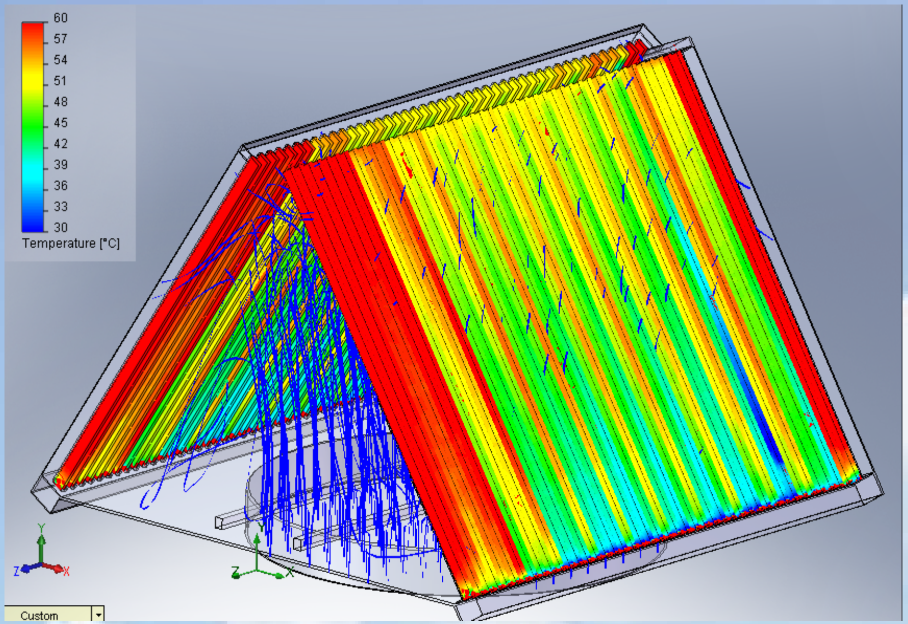
MACCSol

SEVENTH FRAMEWORK PROGRAMME

Current Practice in ACCs

- Suspect to wind effects
- Highly non-uniform flow distribution on air-side





- Lack of quantitative data available in public domain
  - Flow distribution measurements carried out on A-Frame ACC in a ~400MW plant in Ireland
    - Measurements made using thermistor network

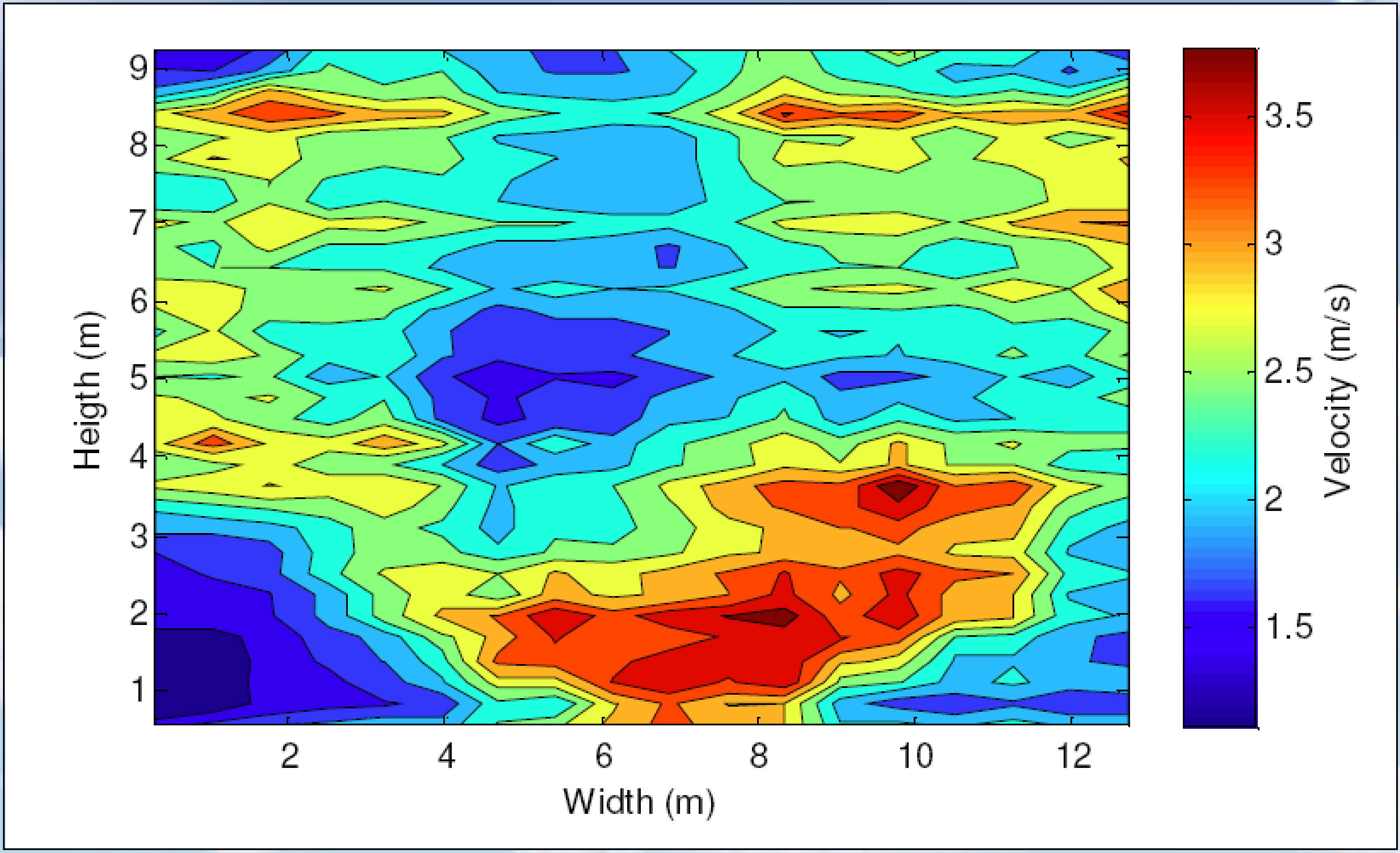
MACCSOL

SEVENTH FRAMEWORK PROGRAMME

Measurements on Conventional ACC

Measurements on Conventional ACC

- Exit velocity field from ACC cell with single ACC fan operational

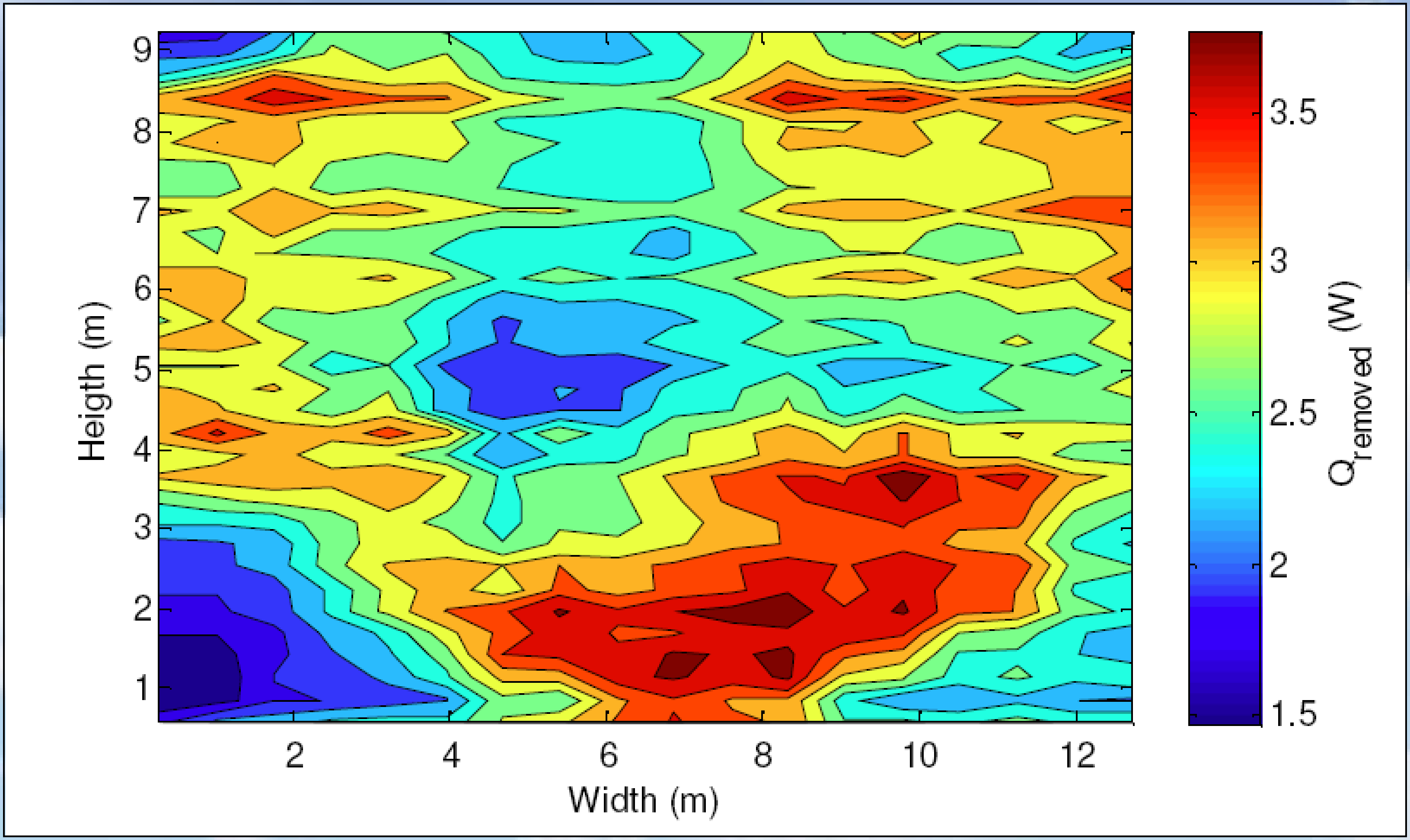


MACCSOL

SEVENTH FRAMEWORK PROGRAMME

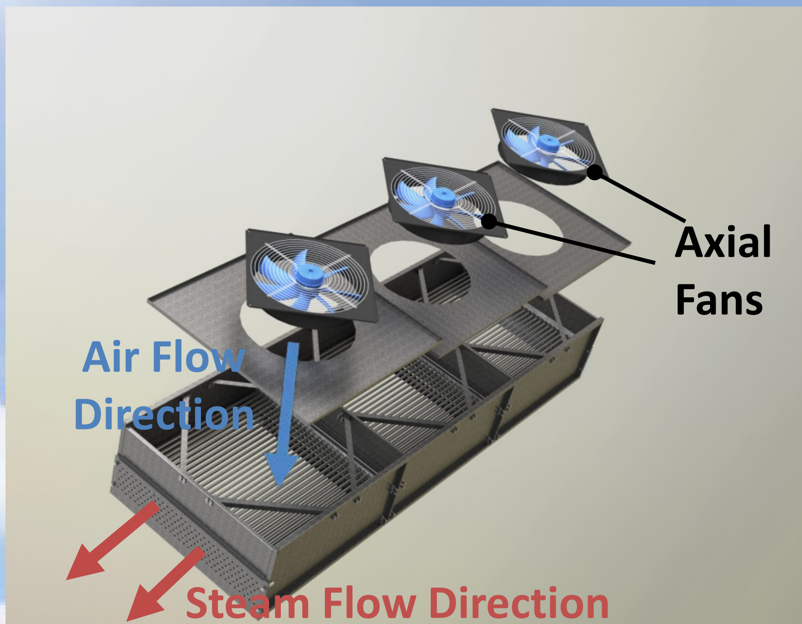
Measurements on Conventional ACC

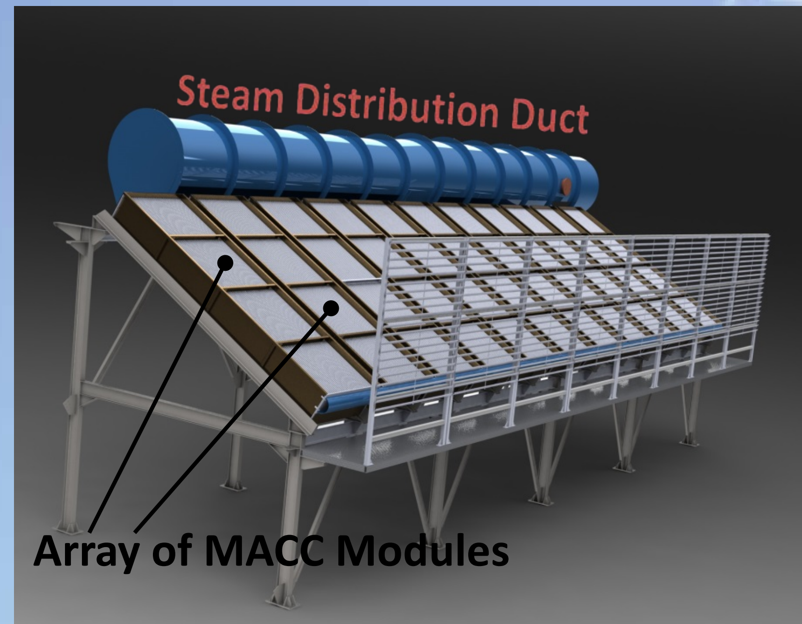
- Heat removal rate from ACC cell with single fan operational



Modular ACC Design

- Modular Air Cooled Condenser – MACC

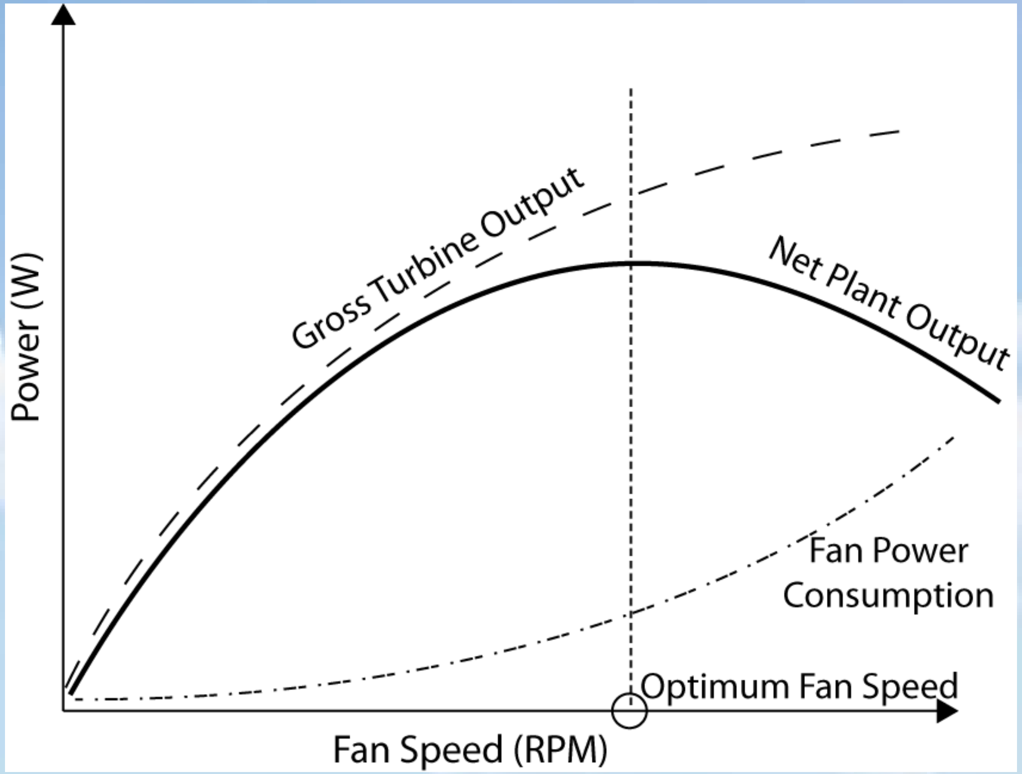




- Modular nature – reduced transport, installation & maintenance costs
  - Beneficial for difficult-to-reach places such as desert CSP sites
- Close proximity of small fans to heat exchanger core ensures uniform air flow over the entire tube bundle
  - “Dead-zones” arising from flow maldistribution are eliminated

Modular ACC Design

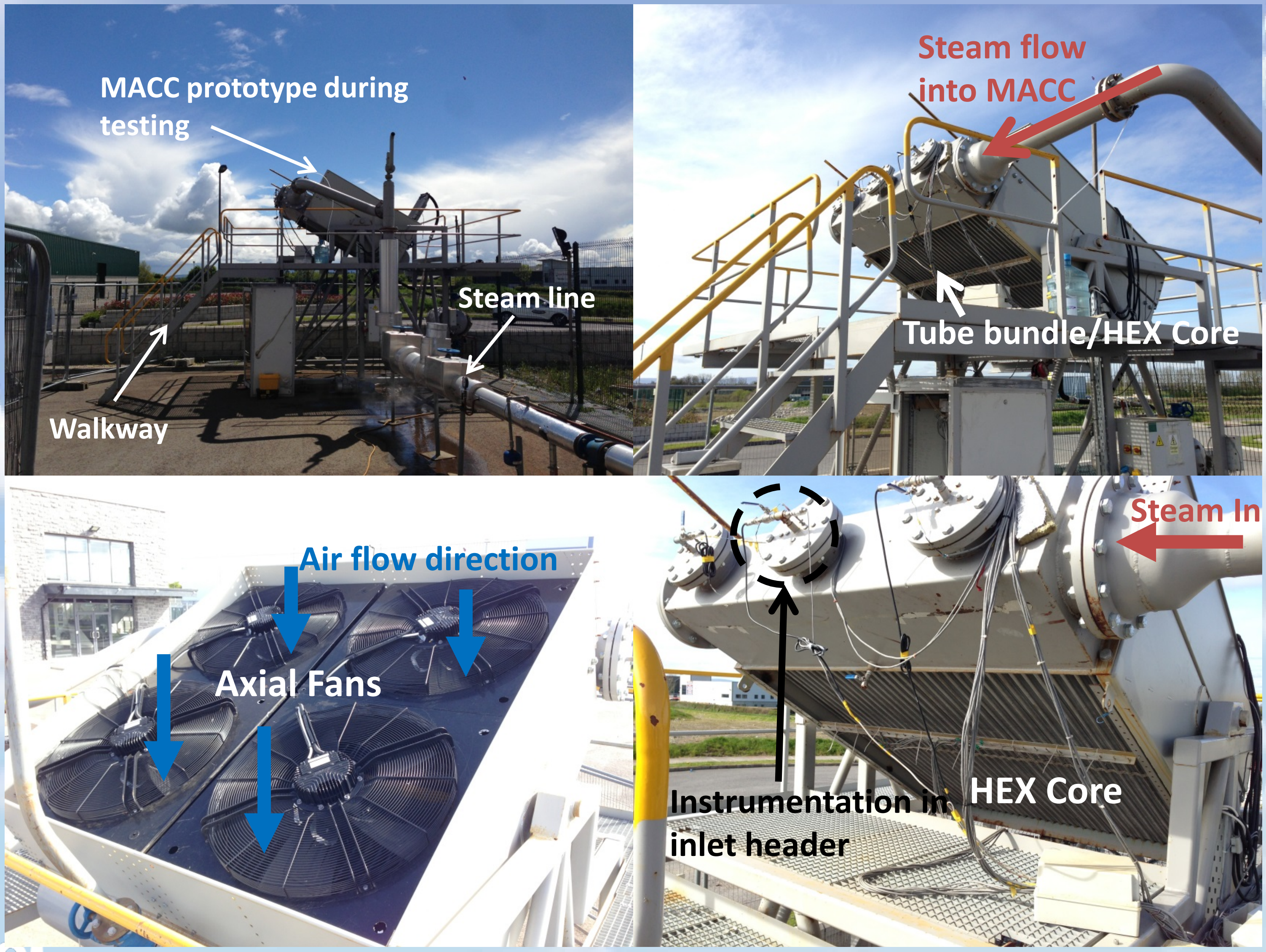
- MACC design incorporates small, speed controllable electric fans
  - Fan speed is continuously variable to maintain optimum condenser conditions irrespective of ambient temperature or steam turbine load
    - Sensors and feedback loop create control algorithm for fans
  - Ability to achieve and maintain an **<u>optimum operating point</u>**
  - Maximise plant output without over-consumption of fan power



Net Power = Gross Power – Fan Power

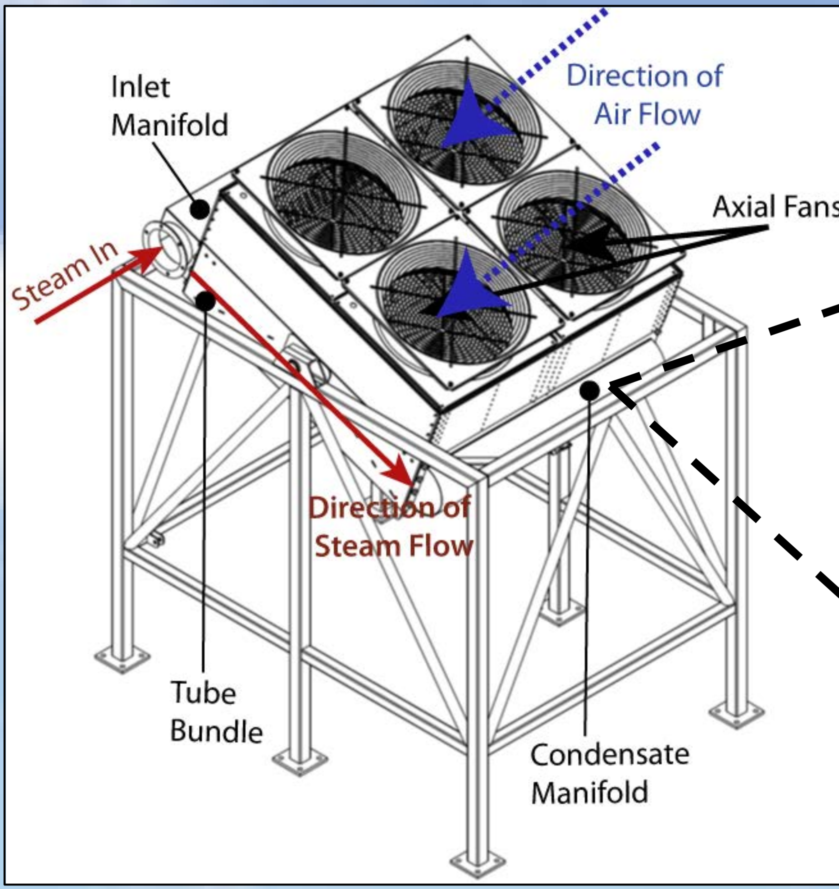
Modular ACC Design

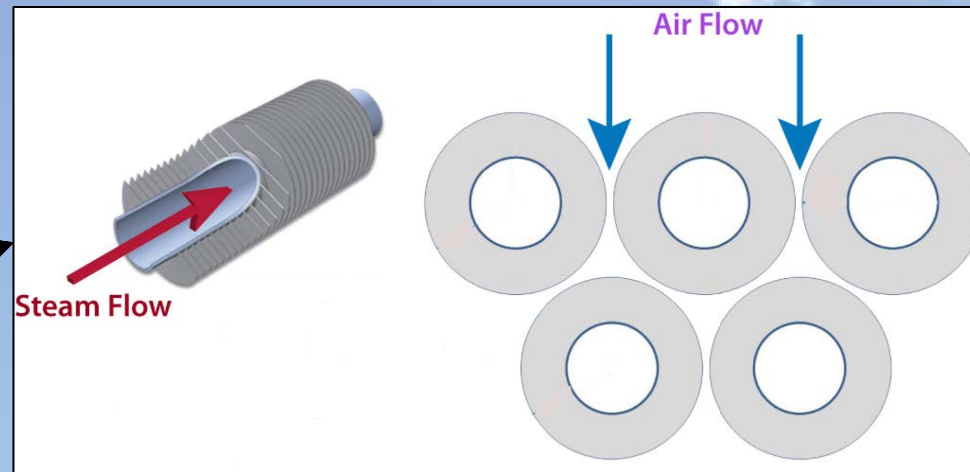
- Full-scale prototype designs have been fabricated and tested on-site in Ireland



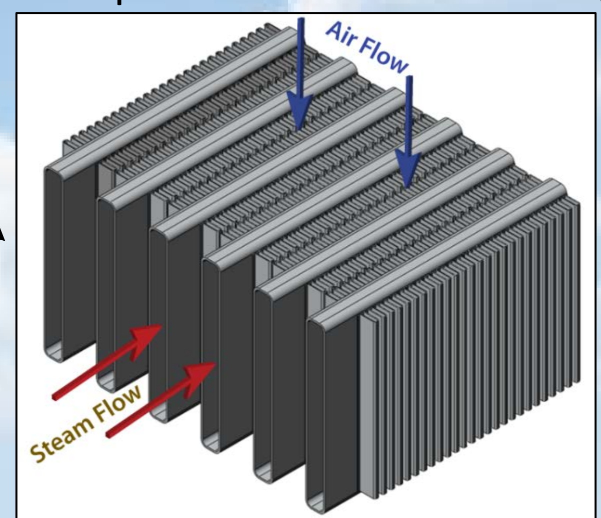
Modular ACC Design

- 3 compact heat exchanger designs have been characterised
  - 6 row circular-finned heat exchanger
  - 4 row circular-finned heat exchanger





- Single row plate-finned heat exchanger



MACCSol

SEVENTH FRAMEWORK PROGRAMME

Experimental Measurements on Prototypes

- Measurements carried out in Ireland
- Test facility to provide slightly superheated steam at approx. 1.5Bar

- Experimental arrangement was modified to facilitate air-side or steam-side testing

MACCSol

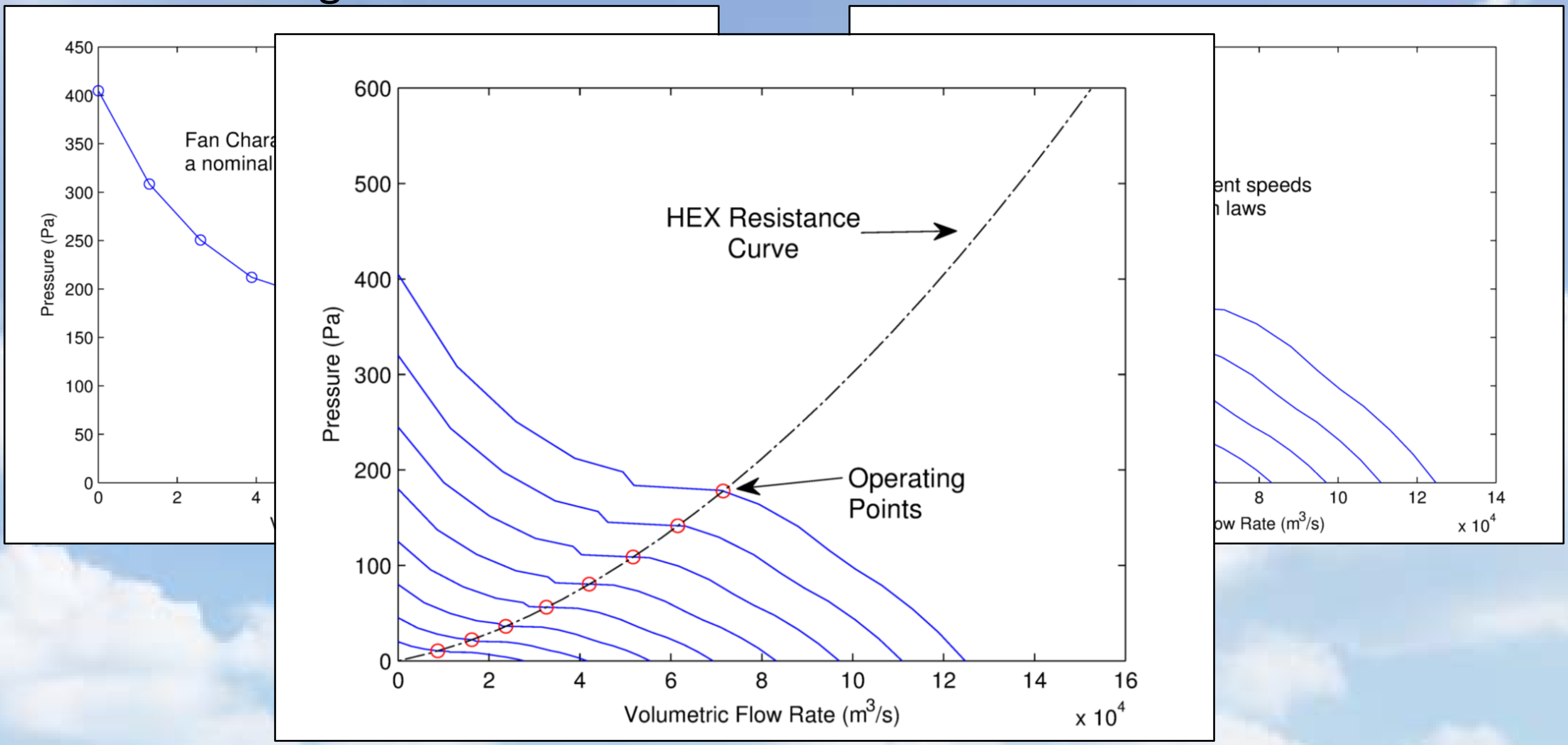
SEVENTH FRAMEWORK PROGRAMME

Air-Side Characterisation of MACC

- Quantify aerodynamic and thermal performance of heat exchanger
  - Friction Factor (Pressure Drop)
  - Nusselt Number (Heat Transfer)
- Empirical correlations are available in literature to predict the performance of various heat exchangers
  - Theory cannot model the complex flow
  - Accuracy of correlations must be verified by experimental means
  - Verification provides confidence in correlations for use in optimisation techniques

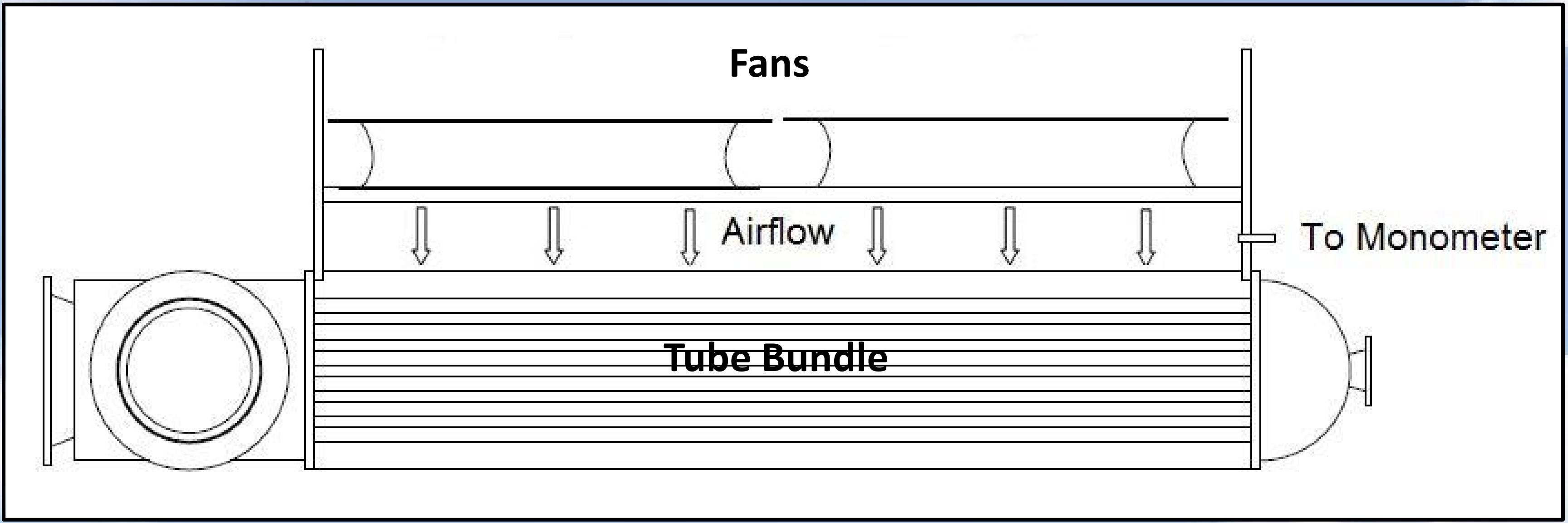
Air-Side Characterisation of MACC

- Correlations are used to predict performance from interaction of fan and heat exchanger



- Intersection of fan curves & resistance curve → HEX operating points
  - Flow rates (volumetric, mass, Reynolds number)
  - Pressure drop (friction factor)
  - Nusselt number (air-side heat transfer coefficient)

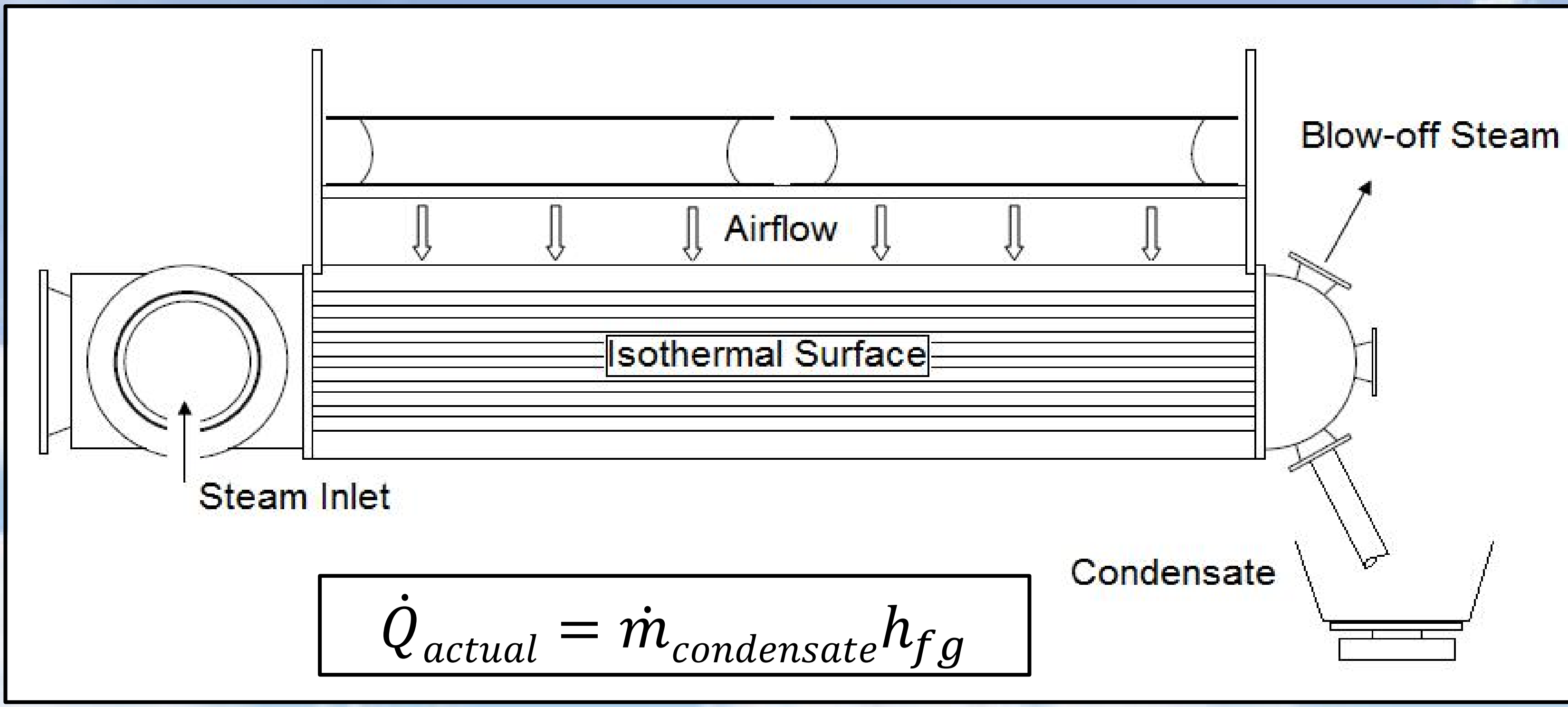
Air-Side Characterisation of MACC – Experimental Procedure (Pressure Drop)



- Fan software to control and measure fan speed and power consumed
  - Vary fan speed incrementally from 100rpm to 1000rpm
- Digital manometer to measure pressure
  - Measures pressure differential between heat exchanger and atmosphere

Air-Side Characterisation of MACC – Experimental Procedure (Heat Transfer)

- *"Kays and London"* test method

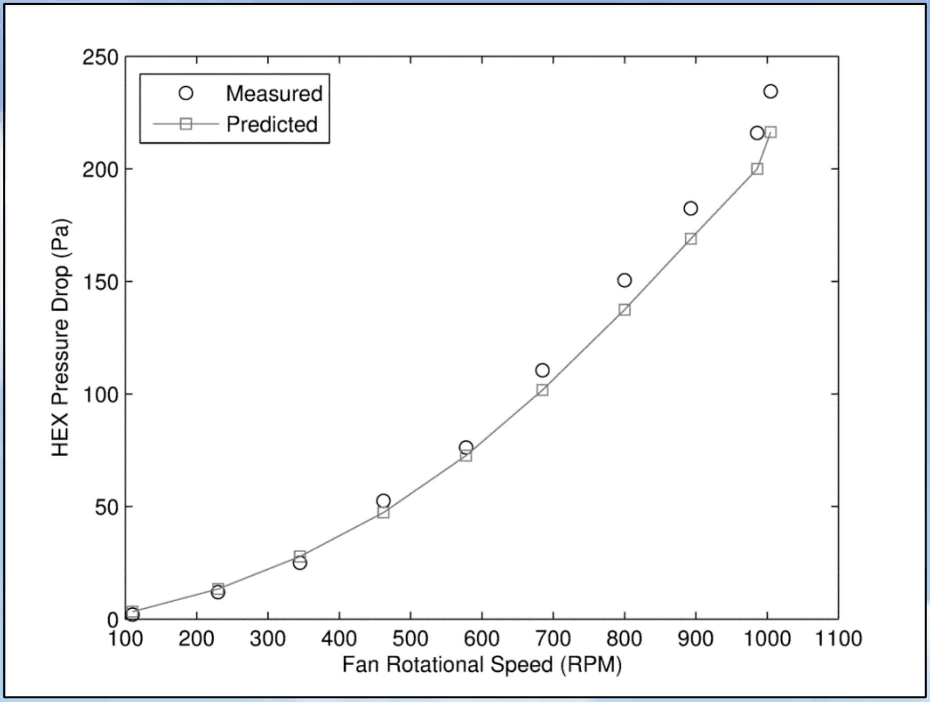


$$\dot{Q}_{actual} = \dot{m}_{condensate} h_{fg}$$

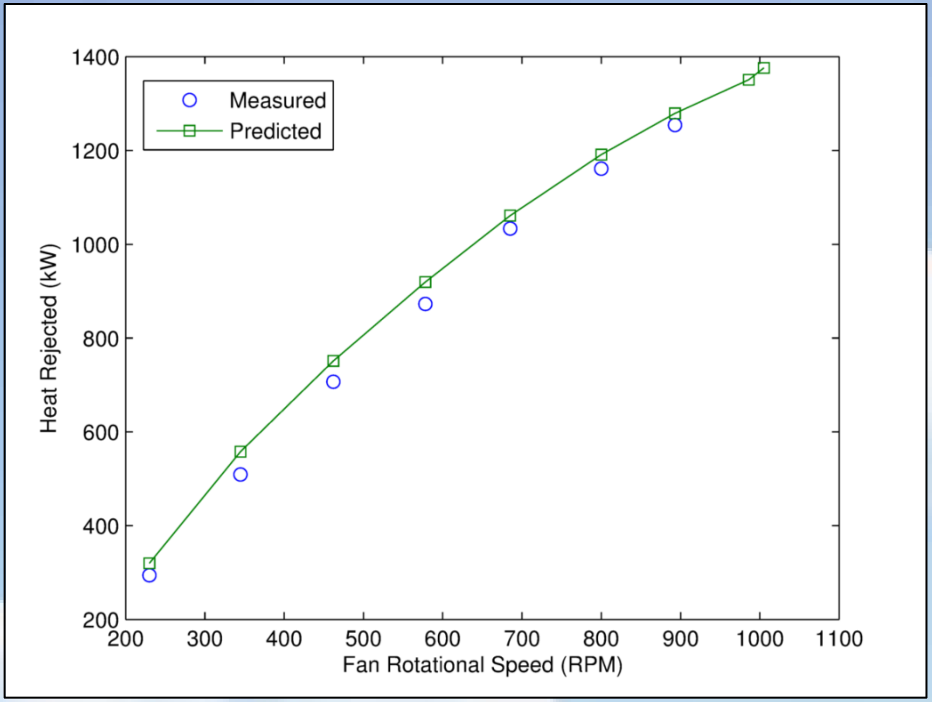
- Slightly superheated steam at inlet
  - Excess steam was forced through to minimise condensate resistance
  - MACC was inclined to promote condensate runoff
- Isothermal conditions

Air-Side Characterisation of MACC – Experimental Results

Pressure Drop



Heat Transfer

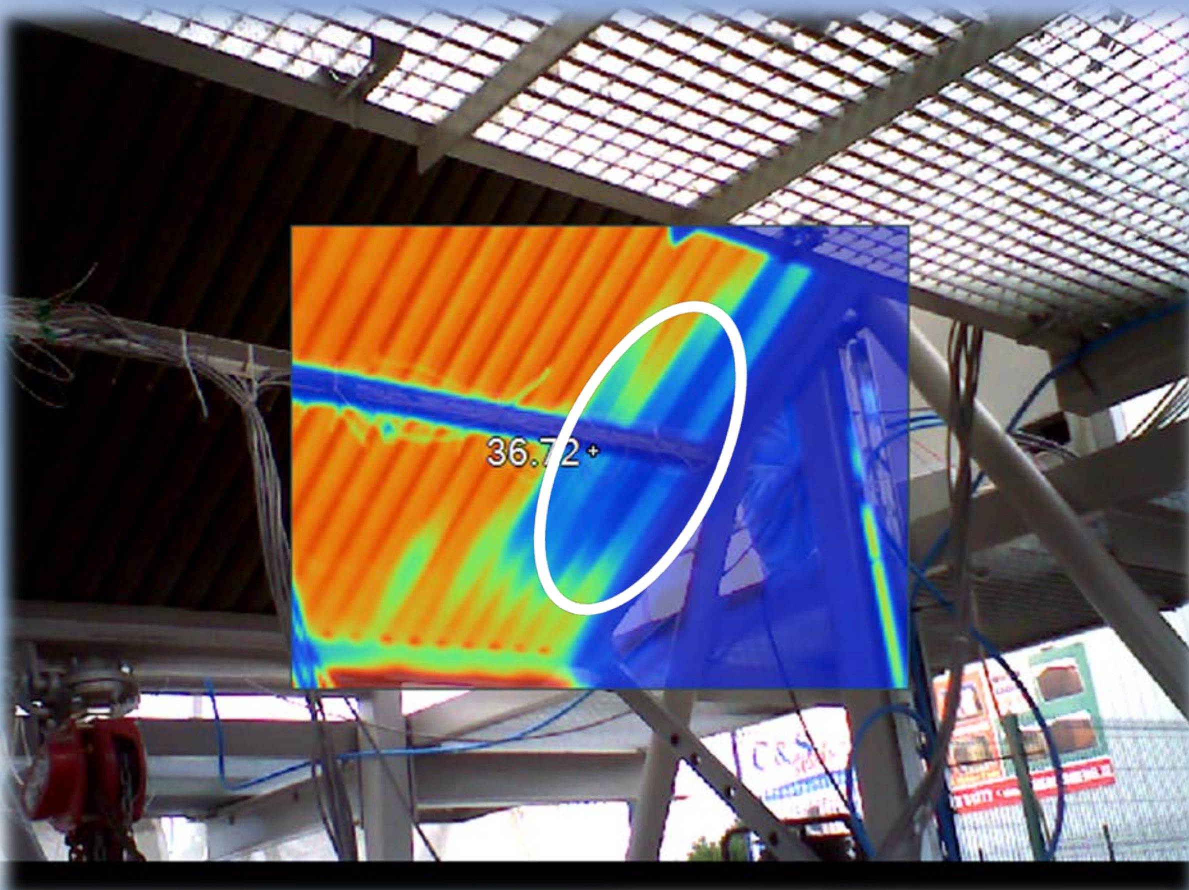


MACCSOL

SEVENTH FRAMEWORK PROGRAMME

Steam-Side Characterisation of MACC

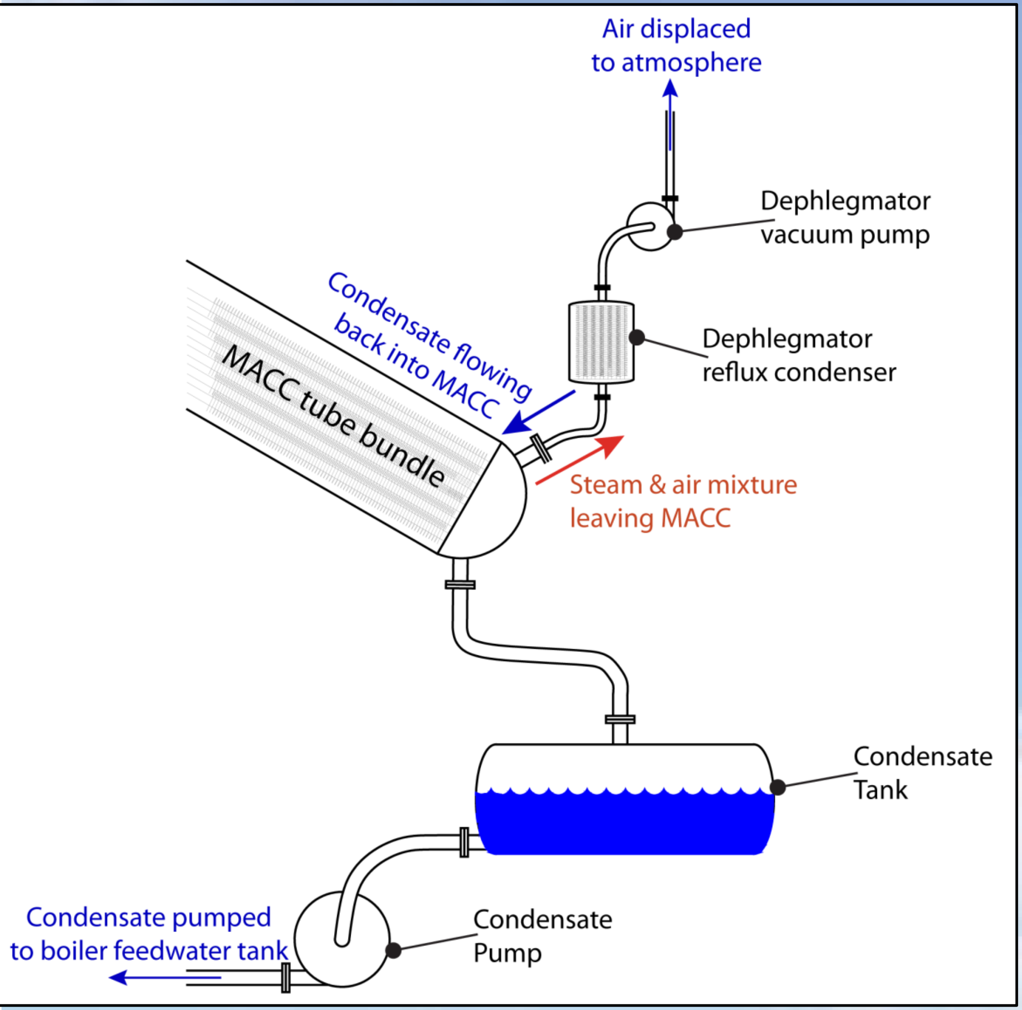
- Quantify the thermal and fluidic performance of the MACC under operational conditions
  - Insight into how the MACC will perform in a power plant
  - Vacuum conditions
  - Air leaks
  - Air-side theory cannot adequately predict condenser performance with condensate-side phenomena such as air leaks, subcooling, etc.
- Backflow was an issue prominent in the multi-row designs
  - Coupled with air ingress, this lead to "*non-condensable blanketing*"



MACCSOL

SEVENTH FRAMEWORK PROGRAMME

Steam-Side Characterisation of MACC – Experimental Arrangement

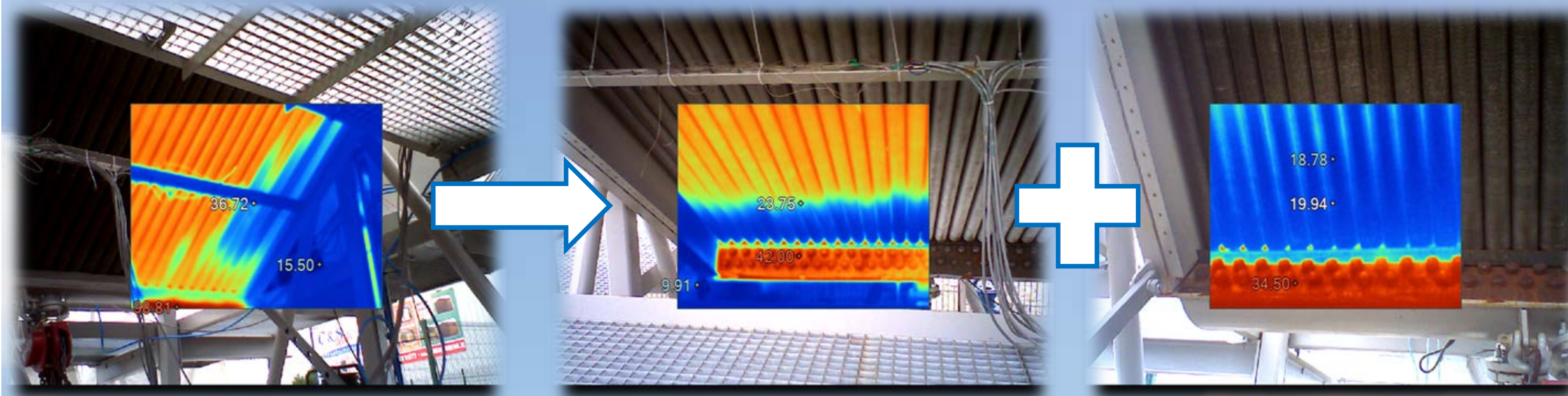


- Solution to air pocket formation – dephlegmator (secondary heat exchanger in series with MACC)
- Excess steam flows from common exit manifold into dephlegmator
- Condensate flows back into MACC exit manifold
- Air leaks are continually displaced by downstream vacuum pump to maintain vacuum

MACCSol

SEVENTH FRAMEWORK PROGRAMME

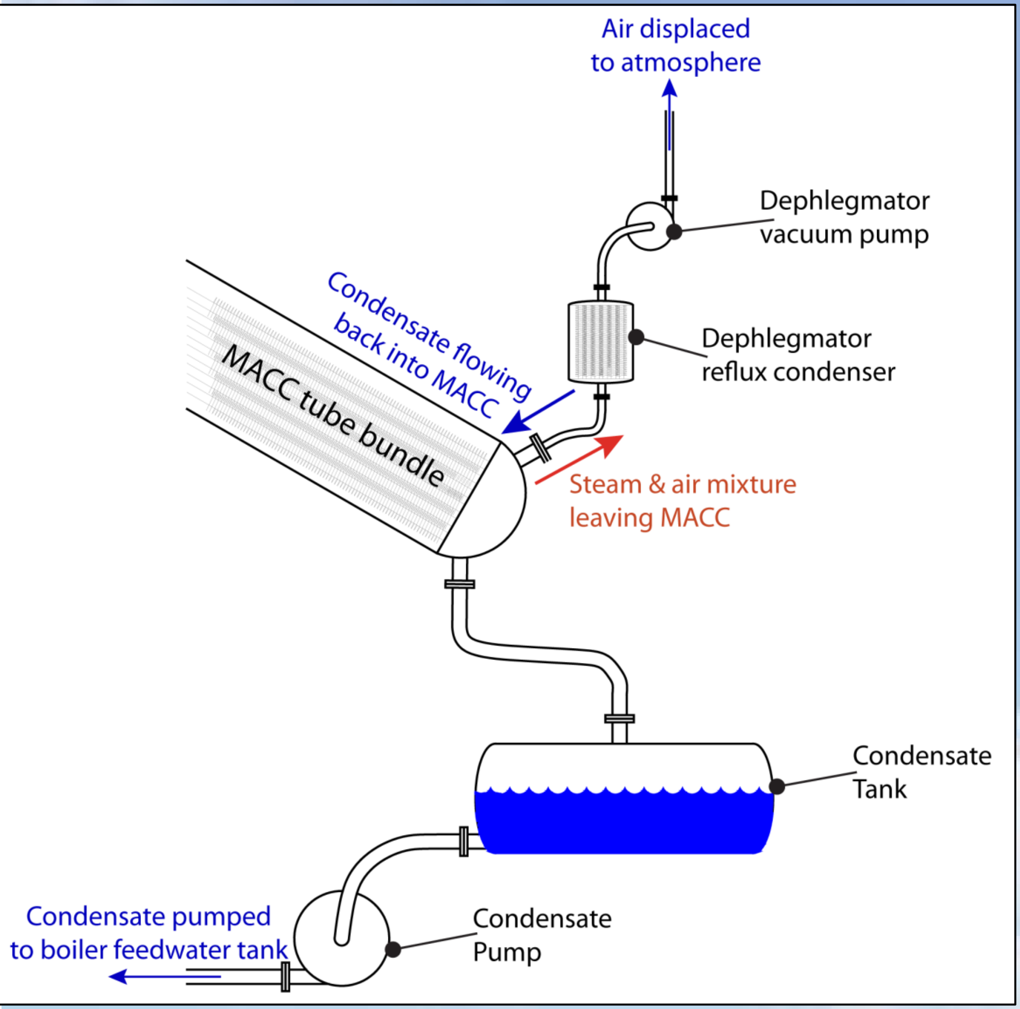
- Backflow is prevented
- Ensures effective heat transfer area is not reduced → Confidence to proceed with testing



MACCSOL

SEVENTH FRAMEWORK PROGRAMME

Steam-Side Characterisation of MACC – Experimental Procedure



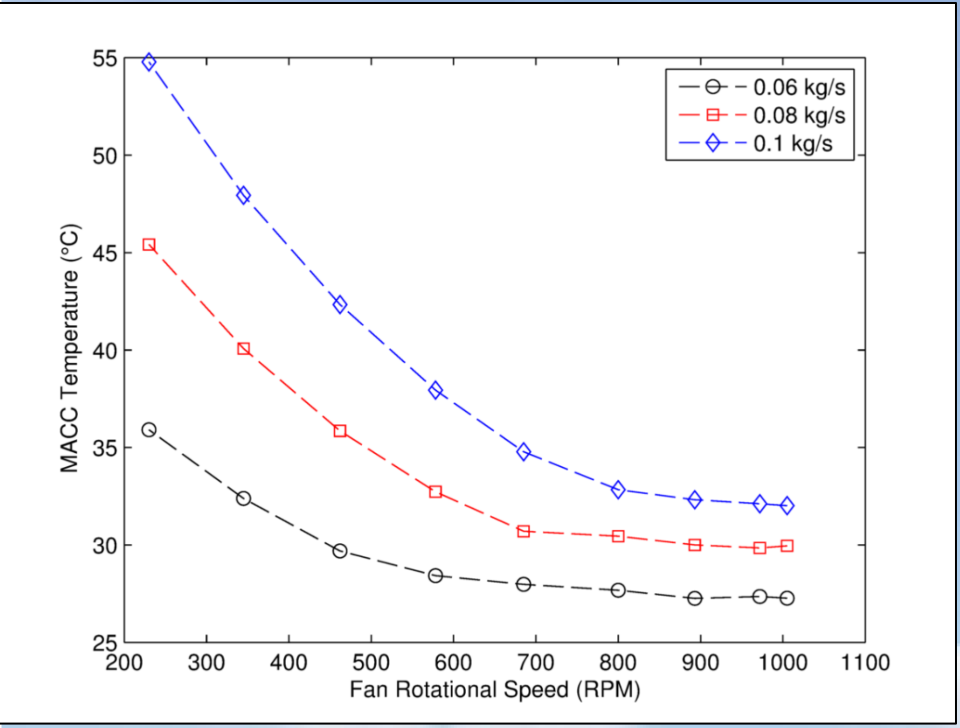
- Purge any air present at startup by forcing steam through tubes
- Confirm isothermal conditions
- Close system and turn-on fans to 1000rpm
- Turn-on vacuum pump and open system to dephlegmator
- Allow for steady-state vacuum
- Resume steam flow and incrementally decrease fan speed from 1000rpm in steps of 100rpm
- Measure variation in MACC temperature & pressure

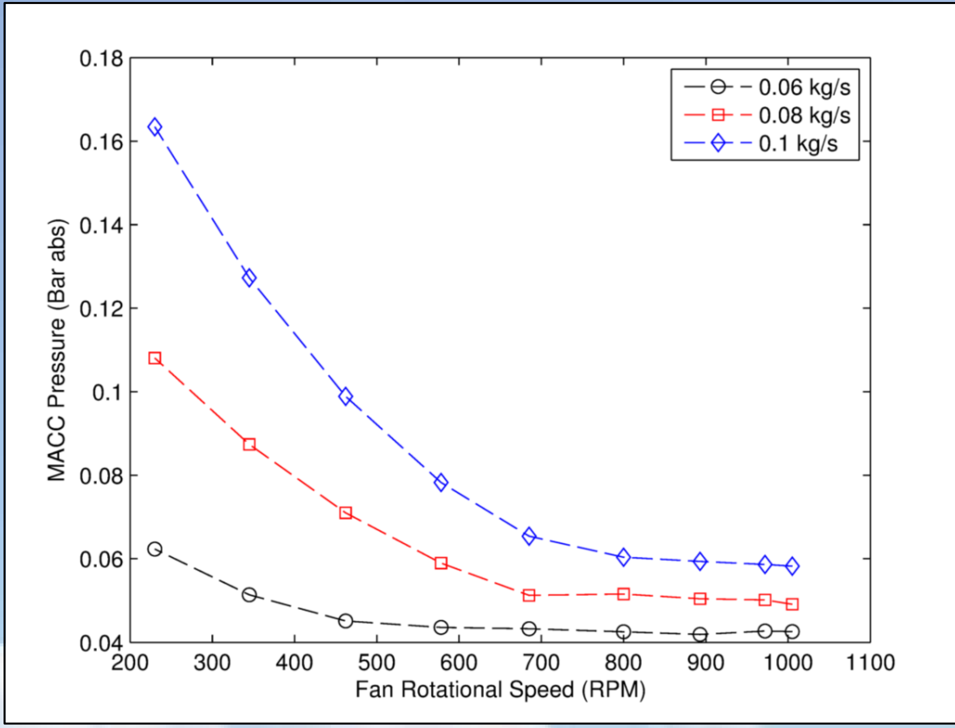
MACCSol

SEVENTH FRAMEWORK PROGRAMME

Steam-Side Characterisation of MACC – Experimental Results

- Variation of temperature and pressure with fan speed for a range of steam flow rates

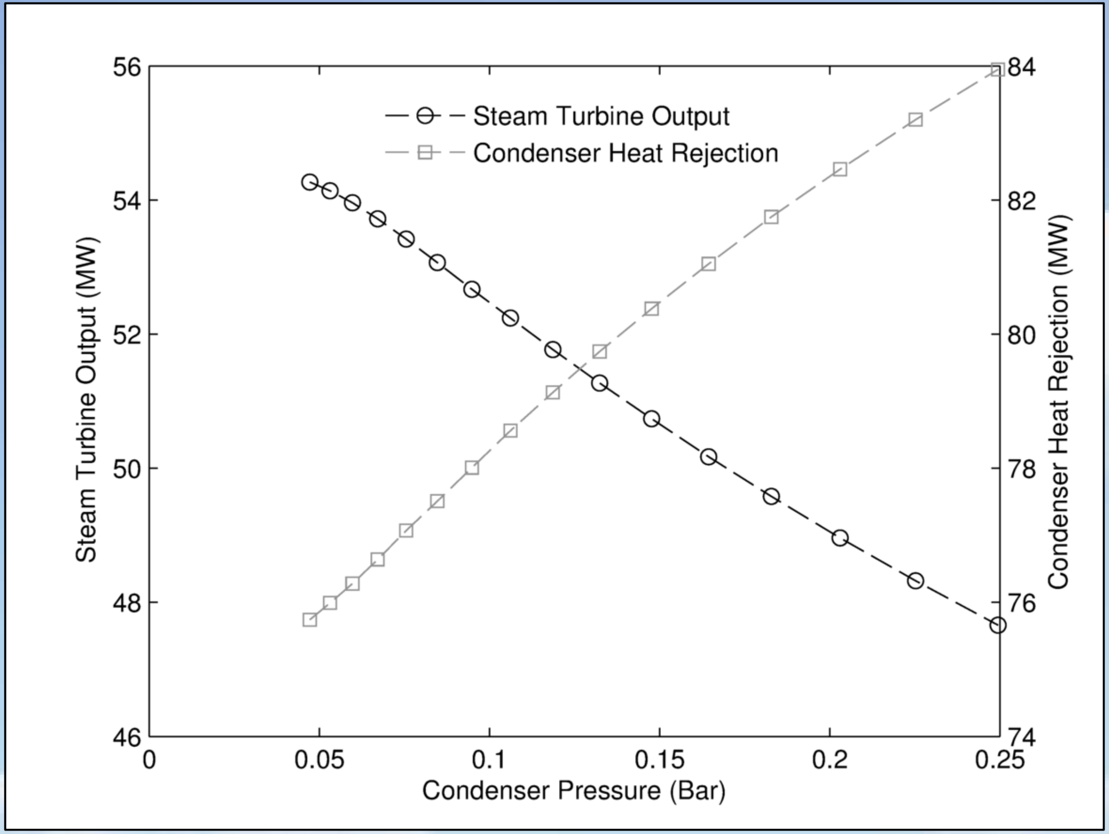




- Results are indicative of how the MACC will be capable of controlling the outlet of a steam turbine in a plant

Impact of MACC on Plant Output

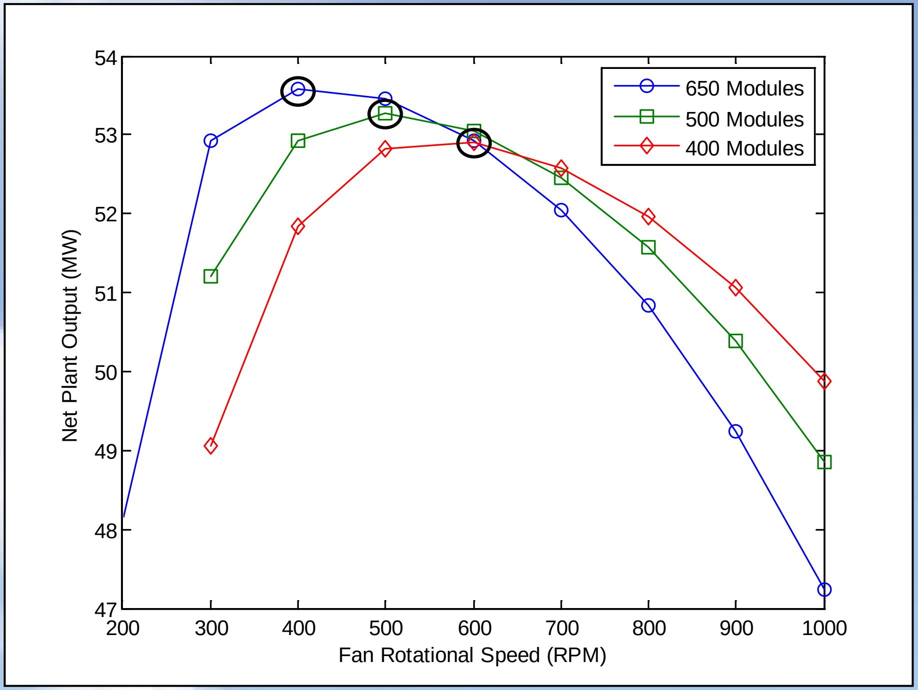
- Determine the effect of installing MACC system on the output of a plant
  - 50MW steam turbine characteristics provided by project partner
- Only concerned with condenser-turbine relationship
- All other power block parameters such as turbine inlet temperature and flow rate were **assumed constant**

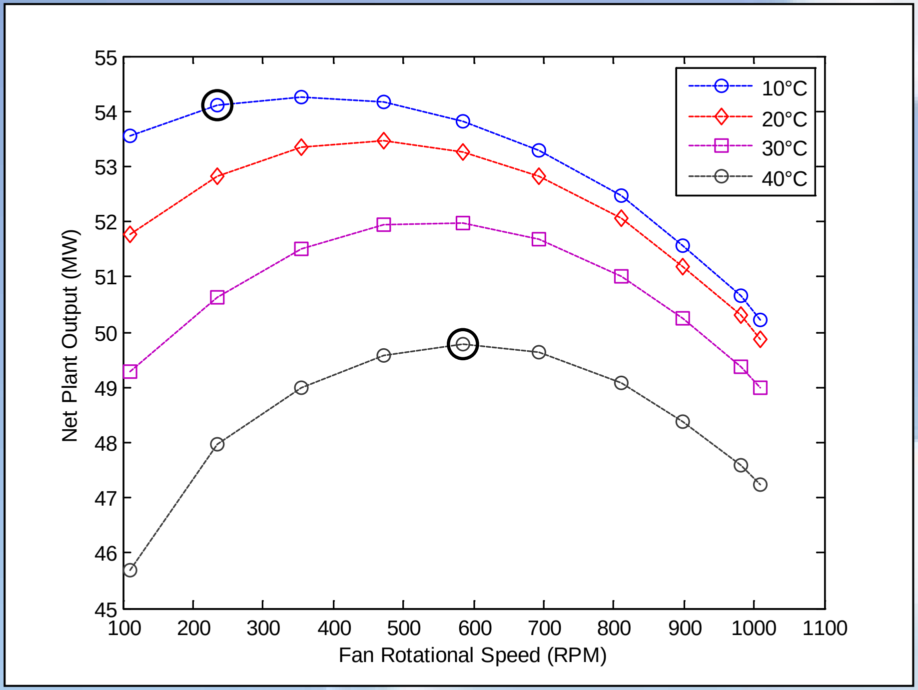


MACCSol

SEVENTH FRAMEWORK PROGRAMME

Impact of MACC on Plant Output





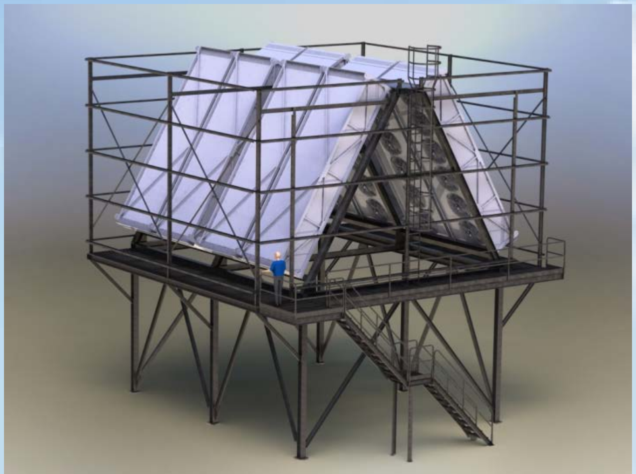
By increasing fan speed from 200 rpm at 10°C to 600 rpm at 40°C, a 1.5MW loss is avoided

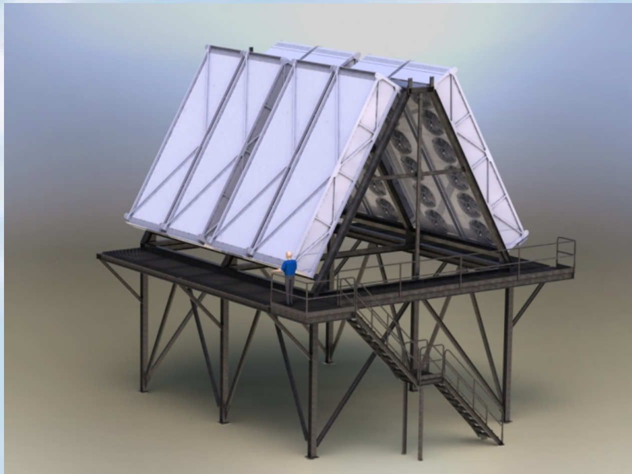
MACCSol

SEVENTH FRAMEWORK PROGRAMME

Current Work

- "Demonstrator" MACC is being fabricated in Ireland and due to be shipped to CSP pilot plant in Australia
- 1.2MW central tower CSP plant
  - Owned and operated by Vast Solar (part of the *Australian Solar Institute*)
  - Will be operated for 18-24 months
  - MACCSol member will be present on site to monitor performance and record data





The End

- Thanks for your time. Any questions/comments?

MACCSol team members visiting Gemosolar "central tower" CSP site in Southern Spain

MACCSol

SEVENTH FRAMEWORK PROGRAMME