Closed-Loop Mist/Steam Cooling for Advanced Turbine Systems

T. Wang (ting.wang@ces.clemson.edu; 864-656-5630)
J.L. Gaddis (nasau@ces.clemson.edu; 864-656-3294)
T. Guo (tguo@ces.clemson.edu; 864-656-7203)
X. Li (xianchl@ces.clemson.edu; 864-656-7179)
Department of Mechanical Engineering
Clemson University
Box 340921
Clemson, SC 29634-0921

Abstract

Closed-loop steam cooling has been identified as a promising method for application to ATS engines. There are, however, many technical challenges which need to be overcome to implement this scheme. One of these challenges is to provide a higher internal heat transfer coefficient than that of the existing scheme without causing excessive steam consumption and flow loss.

The **objective** of this program is to deal with the technical challenges associated with closed-loop steam cooling of gas turbine blades for advanced gas turbine systems. Steam/mist cooling has been proposed to achieve the goal. In this program, both the internal convection heat transfer and the impingement heat transfer of steam/mist cooling will be investigated.

The tasks to be conducted and the achievements which have been made so far are as follows:

<u>Task 1</u>: Design and develop the experimental facility and instrumentation to investigate steam/mist internal flow and heat transfer

This task is a major part of the experimental program and consists of the subtasks of developing a steam/mist system to furnish the needed steam and fine water droplets, a heat transfer test section that represents the cooling channels of the industrial gas turbines, and an atomizing system that generates desired mist flow for the two-phase heat transfer measurement. Currently, the complete experimental system for the internal mist/steam flow and heat transfer study has been set up. Considerable amount of effort has been made in optimizing the atomizing system to obtain the desirable droplet size and distribution from the mixing chamber. One-phase steam-only heat transfer measurement which will be used as the baseline case for the two-phase mist/steam flow has been performed, and satisfactory results have been obtained. Two-phase mist/steam heat transfer measurement is ongoing.

Task 2: **Development of a measurement technique for droplet size**

An existing Laser Doppler Velocimetry (LDV) system has been modified to a phase Doppler Particle Analyzer (PDPA) system. This system measures the water droplets size and velocity distributions in the test section through specially designed, miniature (1 mm x 2 mm) Pyrex windows that are grafted on two tubing-end-blocks, by using a specially designed traversing system that synchronizes and moves the transmitter and the receiver simultaneously. The PDPA system has been verified against the known-size Polymer Latex Suspension (PSL) particles. The measured particle sizes are in good agreement with the actual particle sizes. Effects of laser beam intensity and data sampling rate on the measurement have been investigated.

Task 3: **Design and development of the experimental rig to investigate steam/mist impingement heat transfer on flat and curved surfaces**

A significant effort has been directed toward preparation for testing mist cooling on surfaces (both flat and curved) subject to impingement. Currently, the design for the flat test section has been completed. The test surface is basically a segmented heater which consists of five stainless steel strips with a total resistance of 0.01 ohms. Optical ports (windows) will provide for viewing the mist flow for velocity parallel to the heated surface and for the size distribution of mist particles. The experimental setup is designed in such a way that other configurations for impingement, including rows or arrays of individual jets, can be implemented readily.

Task 4: **Computational study of the two-phase steam/mist flow and heat transfer**

In complement with the experimental program, numerical simulation of the two-phase mist/steam flow will be performed. Effects of the mass ratio of the water droplets and the steam, droplet size and wall flux on the mist/steam heat transfer will be investigated. Comparisons of the numerical results with the current experimental results will be made. Currently, investigation of the various ways to incorporate different kinds of interfacial transport models into the code is being made.

Goals for the next reporting period:

- Complete the design and fabrication of the test section for the mist-impingement heat transfer study.

- Complete the measurements (both the heat transfer measurement and the PDPA measurement) for the 2-phase internal mist/steam flow and heat transfer, and analyze the results.

- Finish the numerical simulation of the two-phase mist/steam internal flow and heat transfer and compare the results with those of the current experiment.

Acknowledgments

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Research Area: Heat Transfer

4 Percent Mist ⇒ 200 Percent Enhancement

Abstract

Closed-loop steam cooling (CLSC) has been identified as a promising method for application to ATS engines.

In this program, **closed-loop mist cooling** techniques have been investigated to overcome the challenges associated with CLSC.

It has been found that mist cooling has a much better heat transfer performance than steam cooling. In fact, by adding fine water droplets (9 micrometers) into the single-phase steam flow, up to **200-percent** increase in heat transfer has been observed, with a droplet mass fraction of only **4 percent**.

Introduction

To achieve ATS goals, a promising technique is **Closed-Loop Steam Cooling (CLSC)**. Advantages of CLSC include:

- No compressed air injection is necessary.
- TIT can be increased without increasing the combustor firing temperature. This is desirable for reducing NO_X emission and increasing turbine thermal efficiency.
- Closed-loop steam cooling is favorable in combined cycle because steam is readily available and the lost heat in cooling can be recovered by the bottom cycle.

Challenges

Challenges for implementing Closed-Loop Steam Cooling include:

- An excessive amount of steam is needed.
- Large coolant pressure loss exists along the cooling passage.
- Clean steam is needed.
- Appropriate sealing and piping of the steam flow must be achieved.

Objectives

The objectives of the project include:

- Providing a much higher coolant heat-transfer coefficient without overcooling the turbine blades.
- Providing a much higher coolant heat-transfer coefficient without inducing great pressure loss.
- Developing effective methods for leading-edge cooling.

Proposed Mist Cooling Scheme:

- Steam/water droplet (5 to 20 micrometers) mixtures
- Dry wall condition

Advantages of proposed scheme

Advantages of the proposed scheme include the following:

- High h value because of (1) interactions between droplets and steam flow, (2) increased C_p value, and (3) latent heat of water.
- Smaller coolant pressure drop than that of steam cooling only.
- A controllable h value.
- Existing blade internal air-cooling structures retained.

- Less coolant mass flow rate than steam cooling.
- Positive results shown by previous related researches.

Experimental Program:

Task 1: Design and development of the experimental facility for steam/**mist internal flow** and heat transfer.

Subtask 1.a Development of mist generation system.

Subtask 1.b Development of mixing chamber.

Subtask 1.c Test section design.

Task 2: Design and development of the experimental facility to investigate steam/**mist impingement** heat transfer on flat and curved surfaces.

Task 3: Development of a measurement technique for droplet size and its distribution.

Computational Program:

- Two phase (droplet/steam) flow modeling.
- Numerical simulation using commercial CFD code.

Major Progress 1997

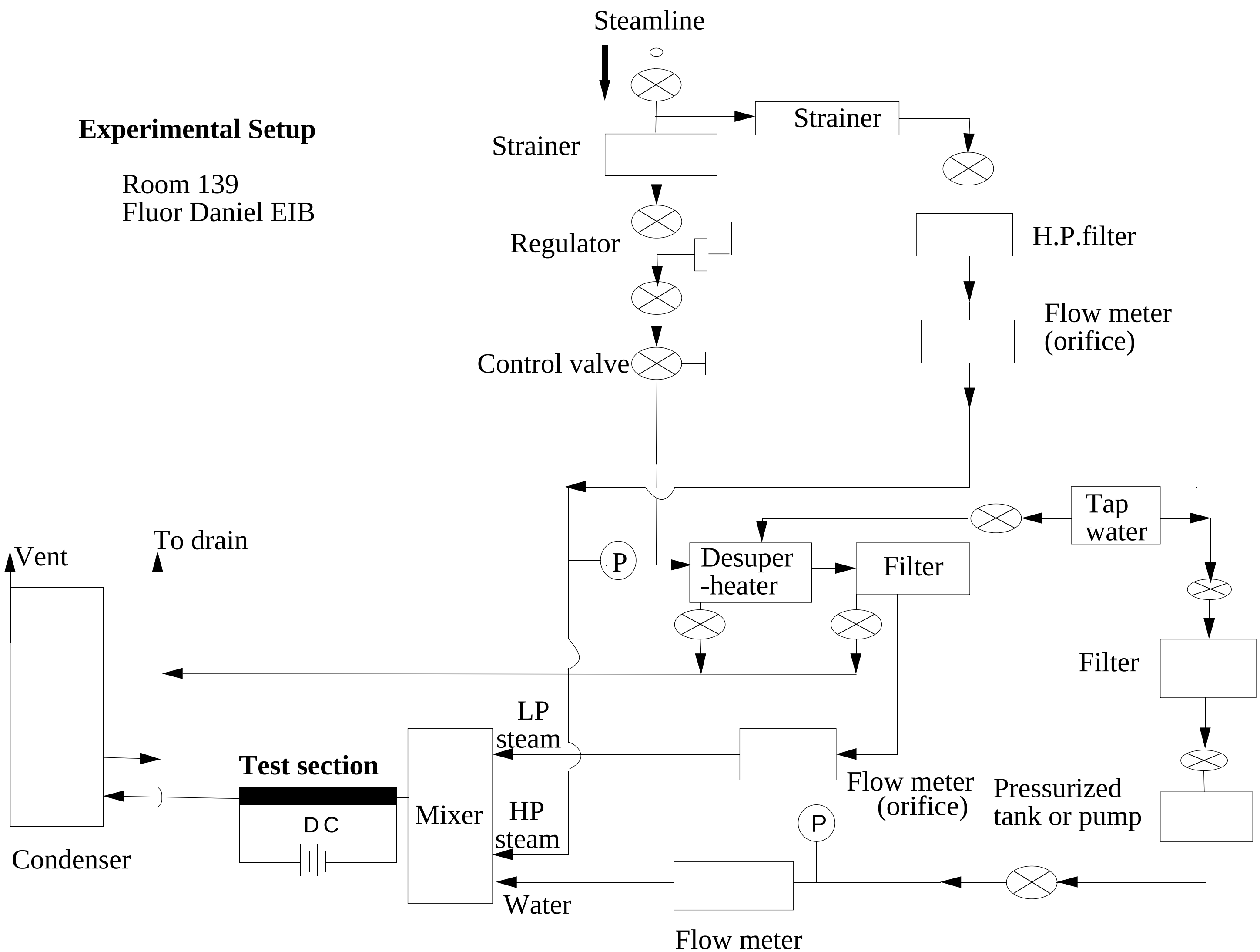
- The design and fabrication of the experimental facility and test section for internal mist flow has been completed.
- Fabrication of the test section for mist impingement heat transfer is near the final stage.
- Measurements (including both the heat transfer measurement and the droplet size and velocity measurement) for internal mist flow are underway.
- Two mist generating systems have been tested.
- Preliminary results show that mist cooling is a promising technique.

Collaborations

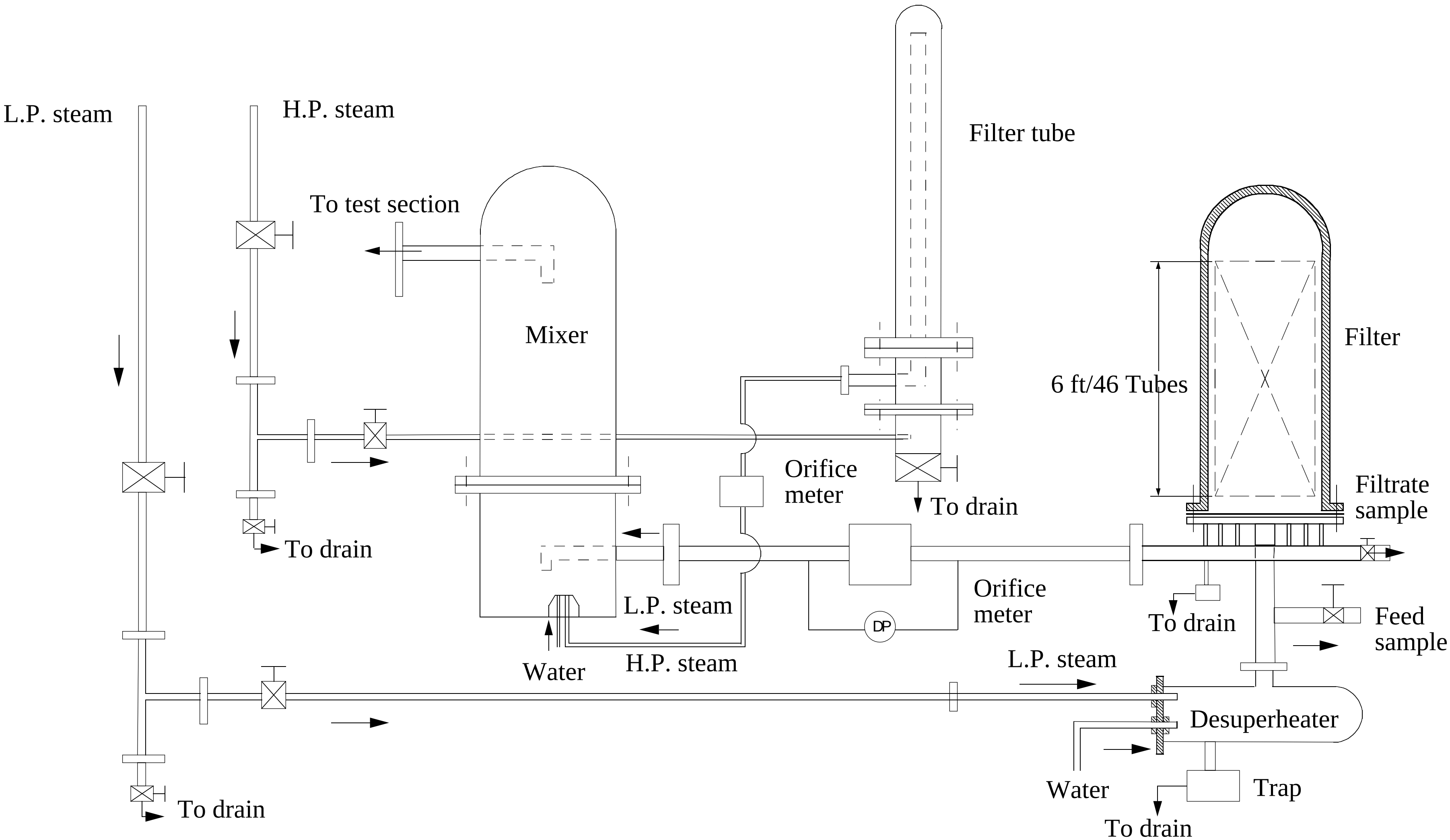
- **GE-CRD, Aircraft, Power Generation** to provide gas-turbine heat-transfer information; advise on mist-cooling concept.
- **Westinghouse** to provide gas turbine cooling, cycle, and combustion information on ATS program.
- **Allied Signal** to discuss general gas turbine heat transfer challenges.
- **Allison** to provide experience on two-phase flow blade cooling.
- **Pratt & Whitney** to provide insights on aeroderivative gas turbine and HAT cycle.

Research Plans for Next Year

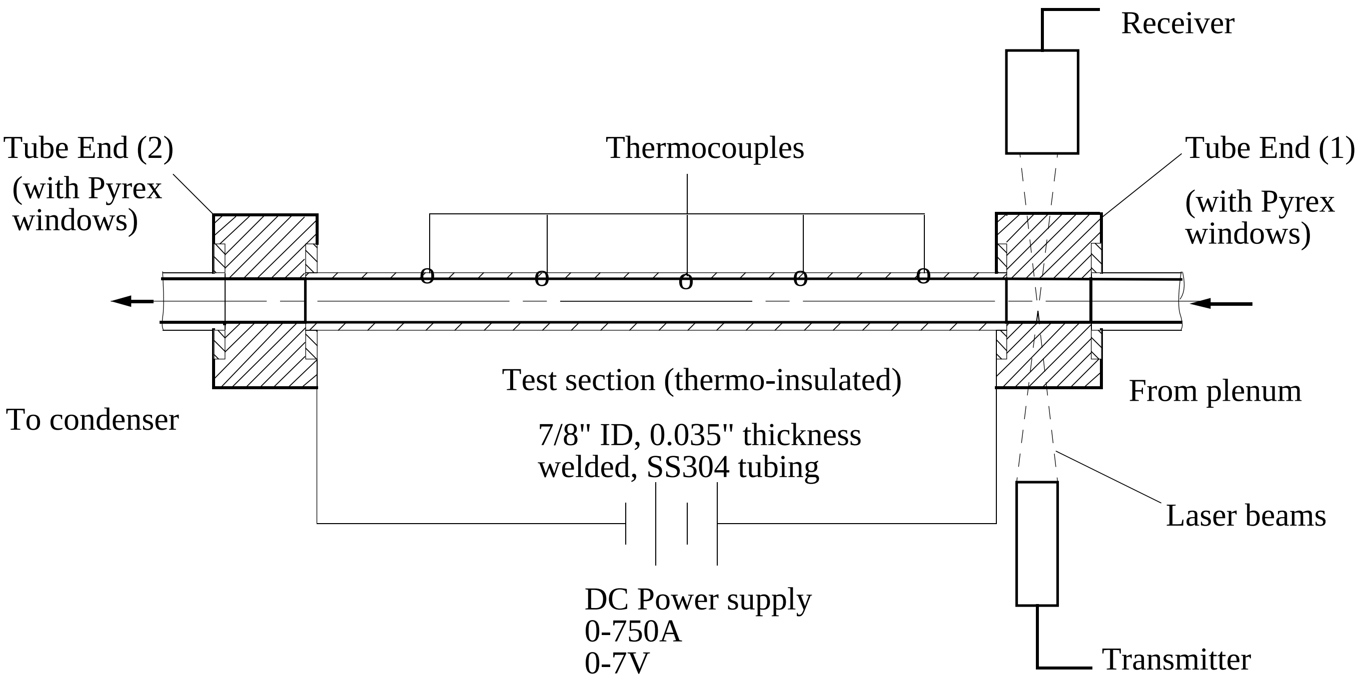
- To complete the measurements (including both the heat transfer measurement and the PDPA measurement) for internal mist flow and analyze the results.
- To complete the study for internal mist flow heat-transfer over a 180-degree circular bend.
- To complete the study for mist impingement heat transfer.
- To compare the experimental data with the CFD results.

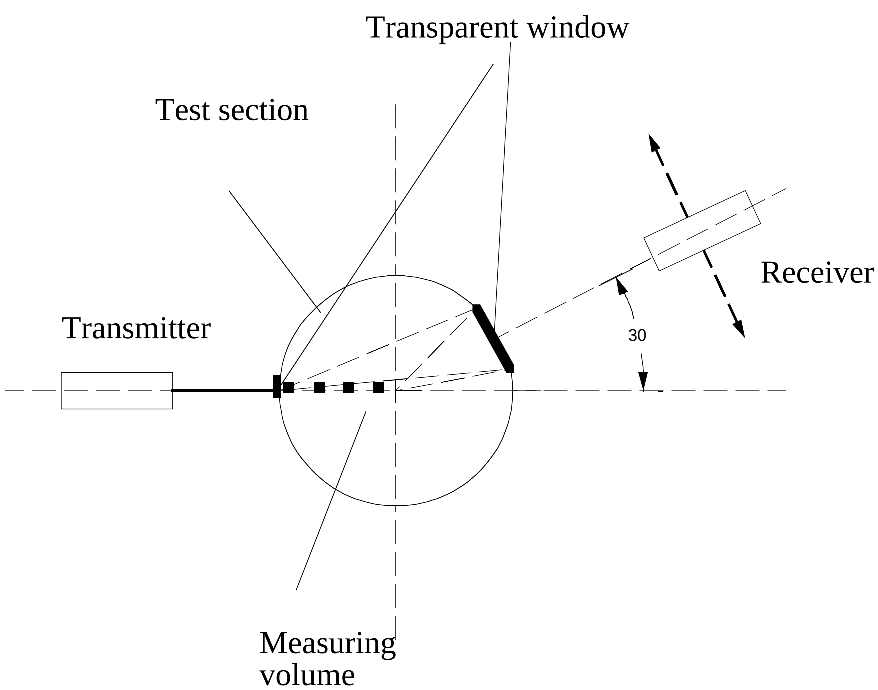


Layout of the experiment facility

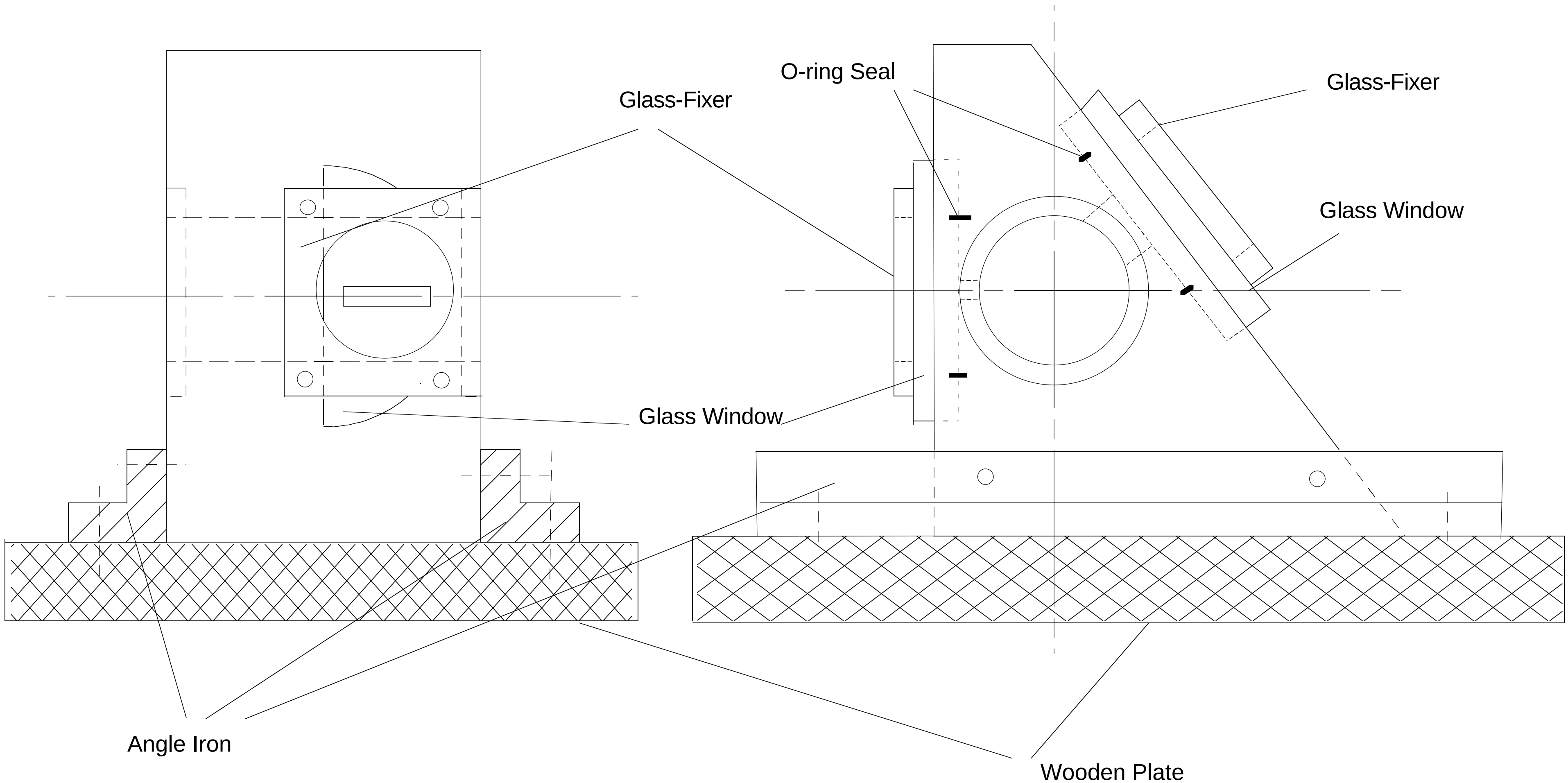


Steam system piping detail

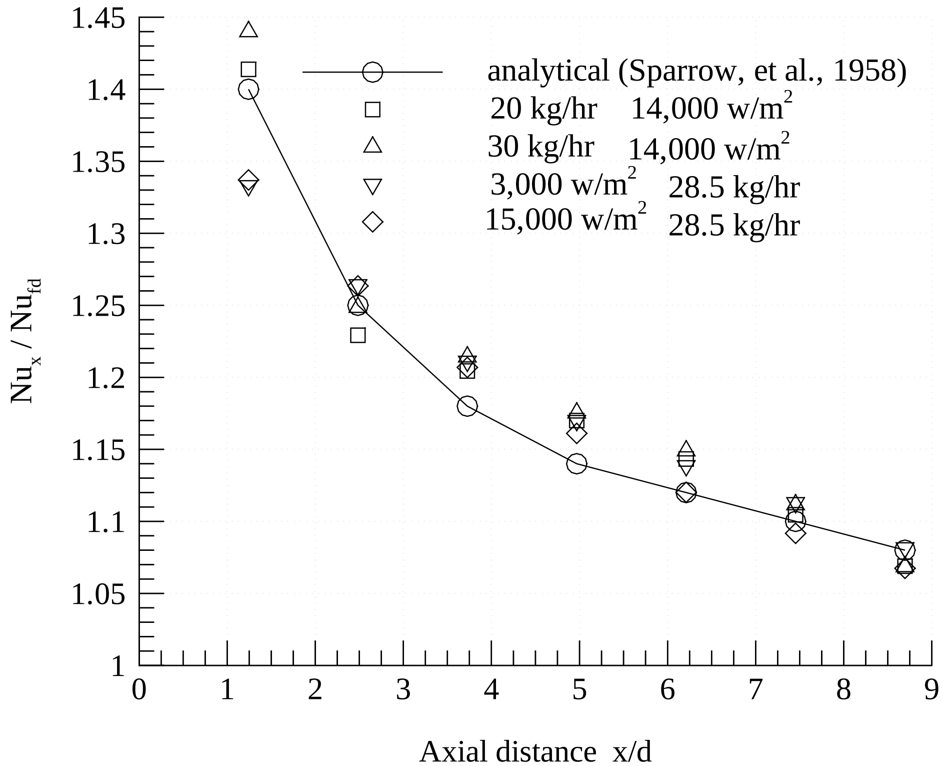




Test section design



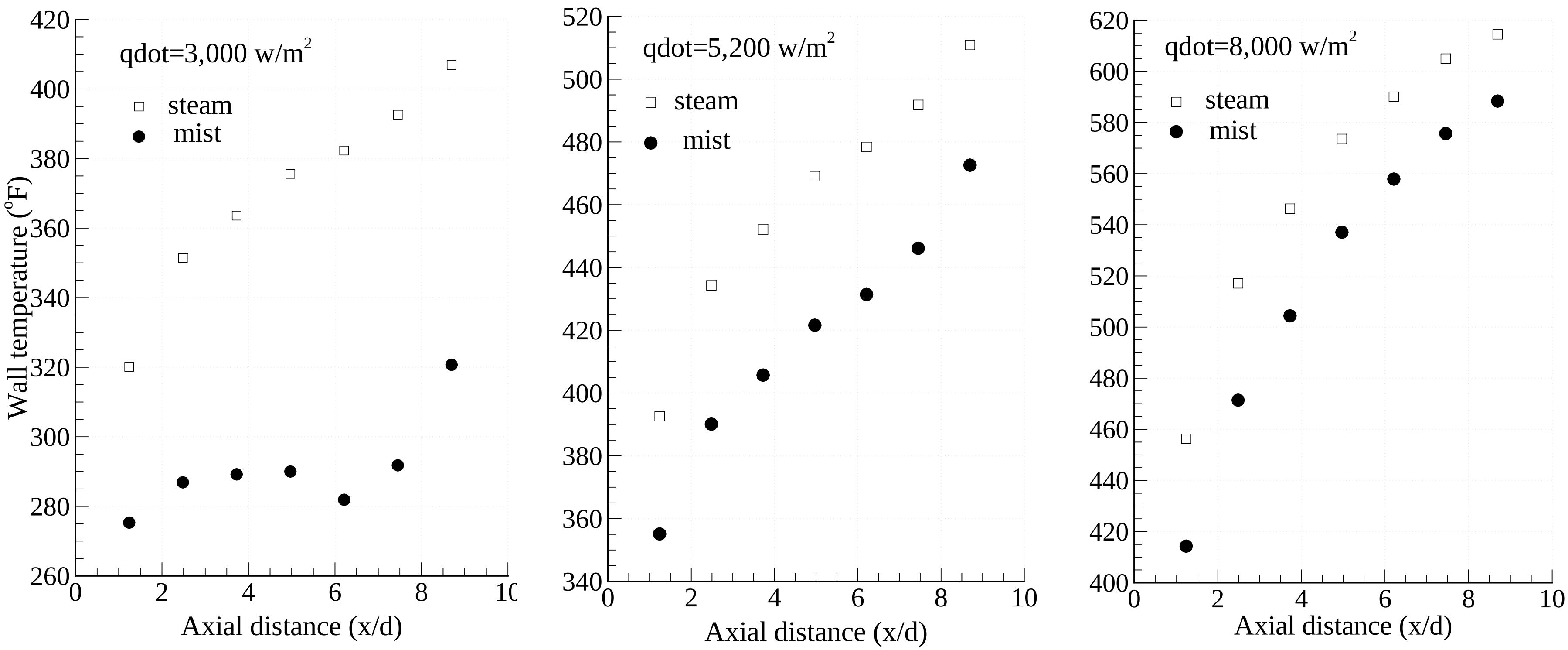
Tube End Assembly



Comparison of experimental and analytical results of the thermal entrance region heat transfer for steam-only flow

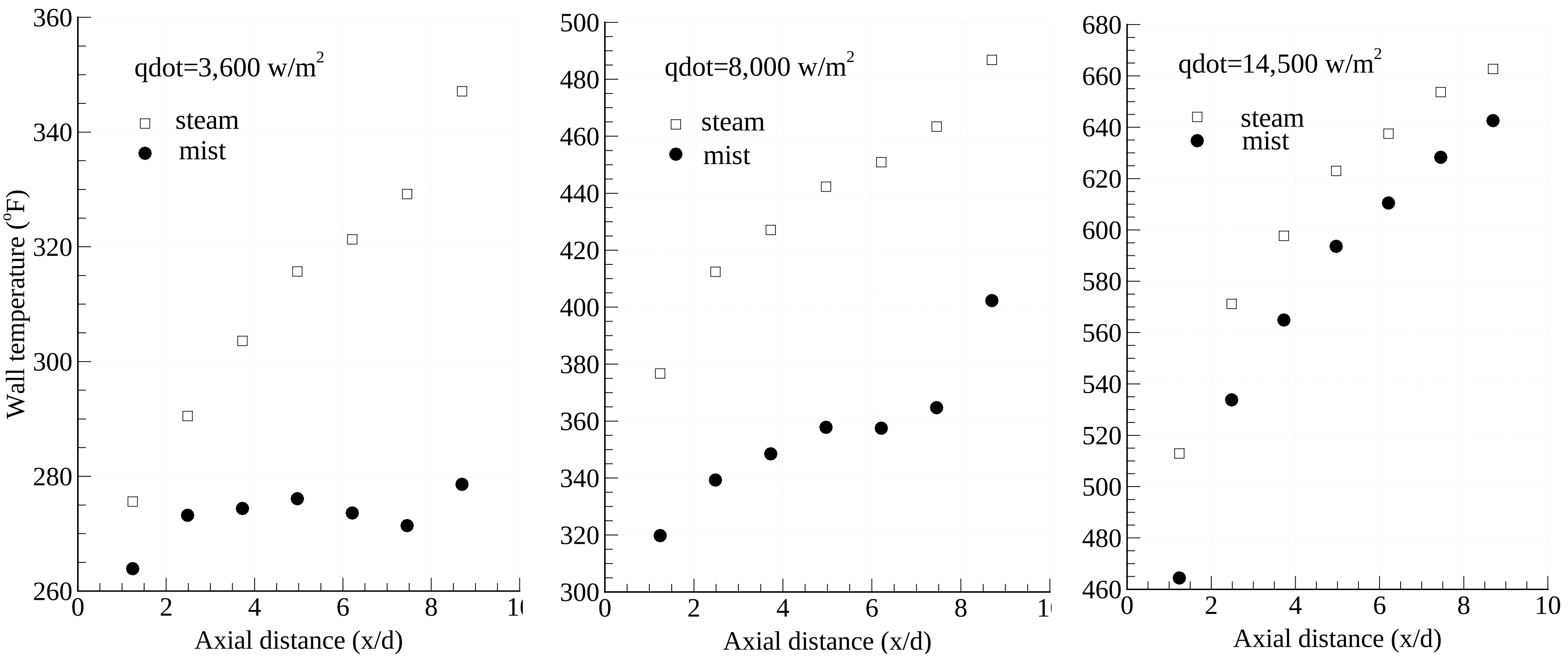
Mist Flow Heat Transfer

Steam Reynolds number:	Re = 10,000
Droplet mass ratio:	m_l / m_s = 4%
Droplet arithmetic mean diameter:	d_{10} = 9 microns



Mist Flow Heat Transfer

Steam Renolds number:	Re = 20,000
Droplet mass ratio:	$m_l / m_s = 2\%$
Droplet arithmetic mean diameter:	d_{10} = 9 microns

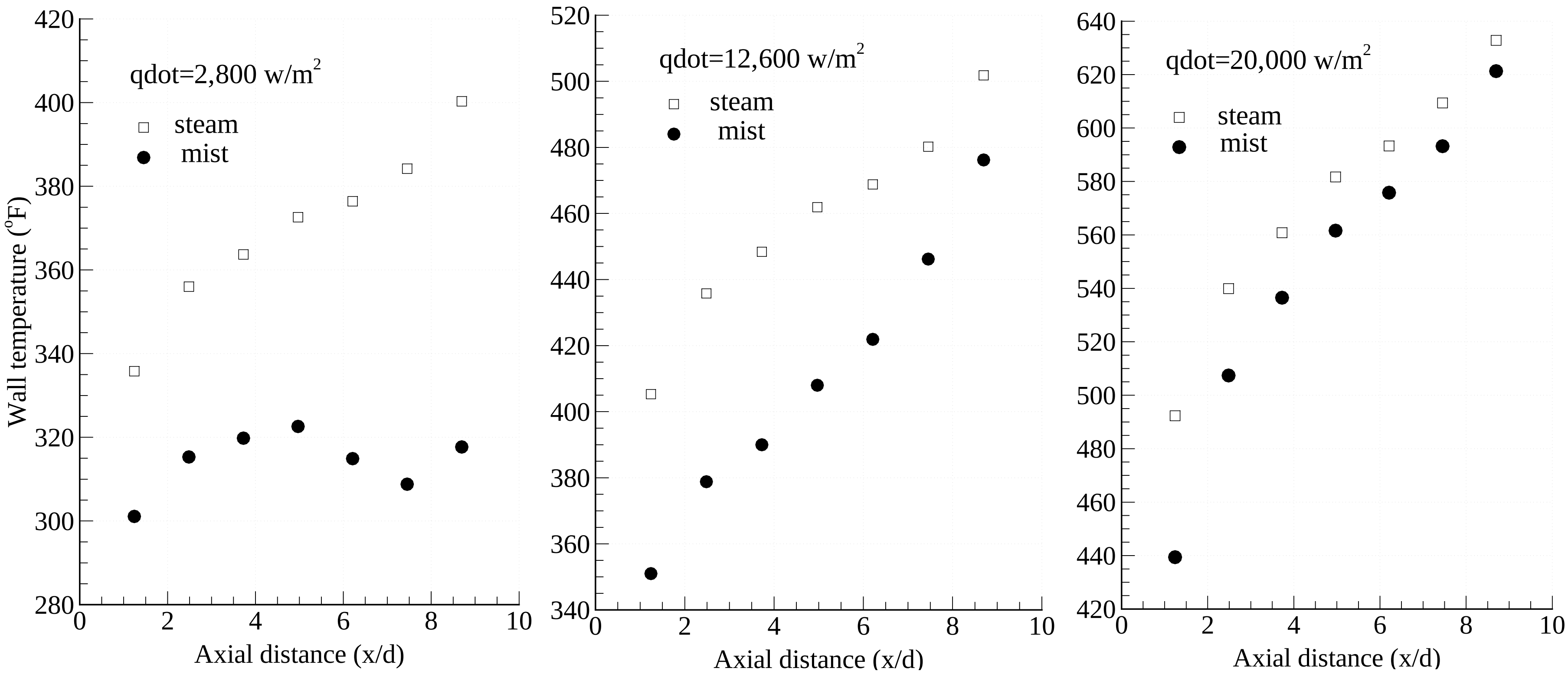


Mist Flow Heat Transfer

Steam Reynolds number: Re = 35,000

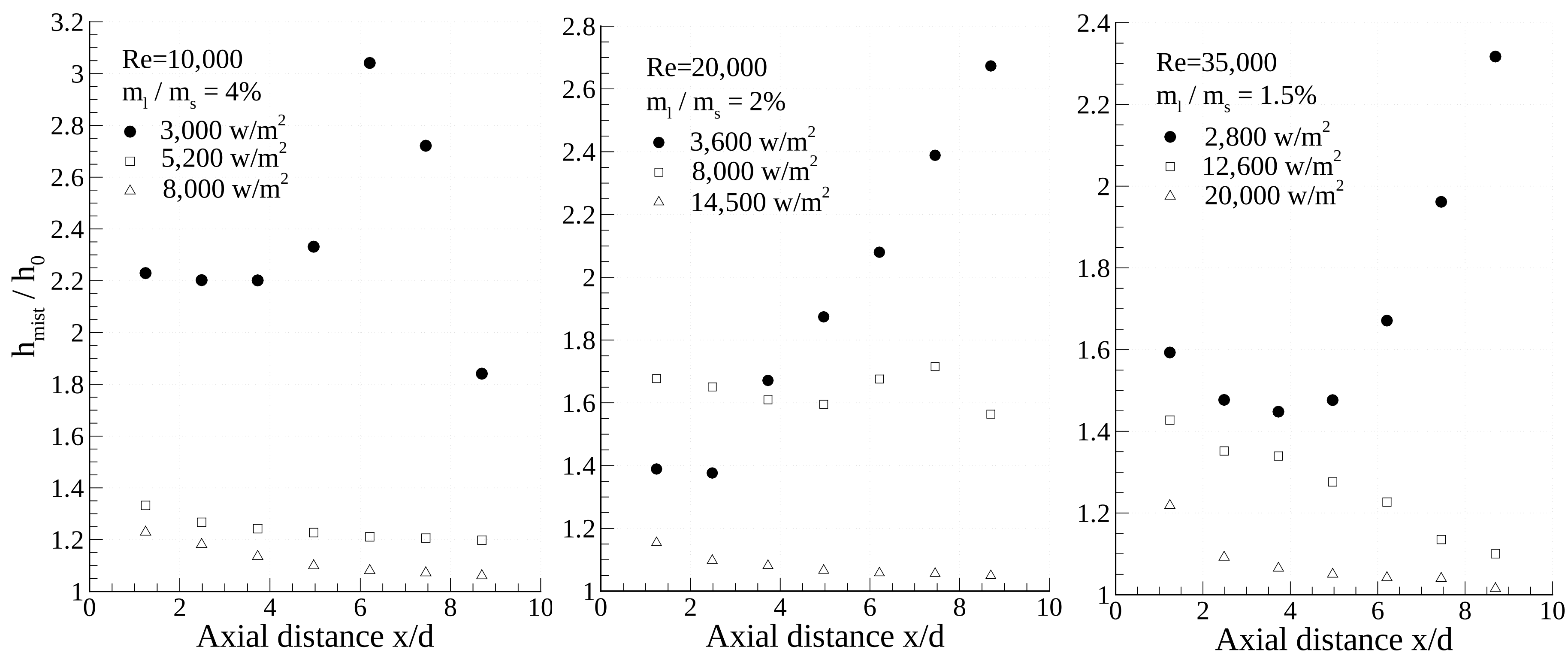
Droplet mass ratio: $m_l / m_s = 1.5\%$

Droplet arithmetic mean diameter: $d_{10} = 9$ microns



Heat Tansfer Coefficient for Mist Flow

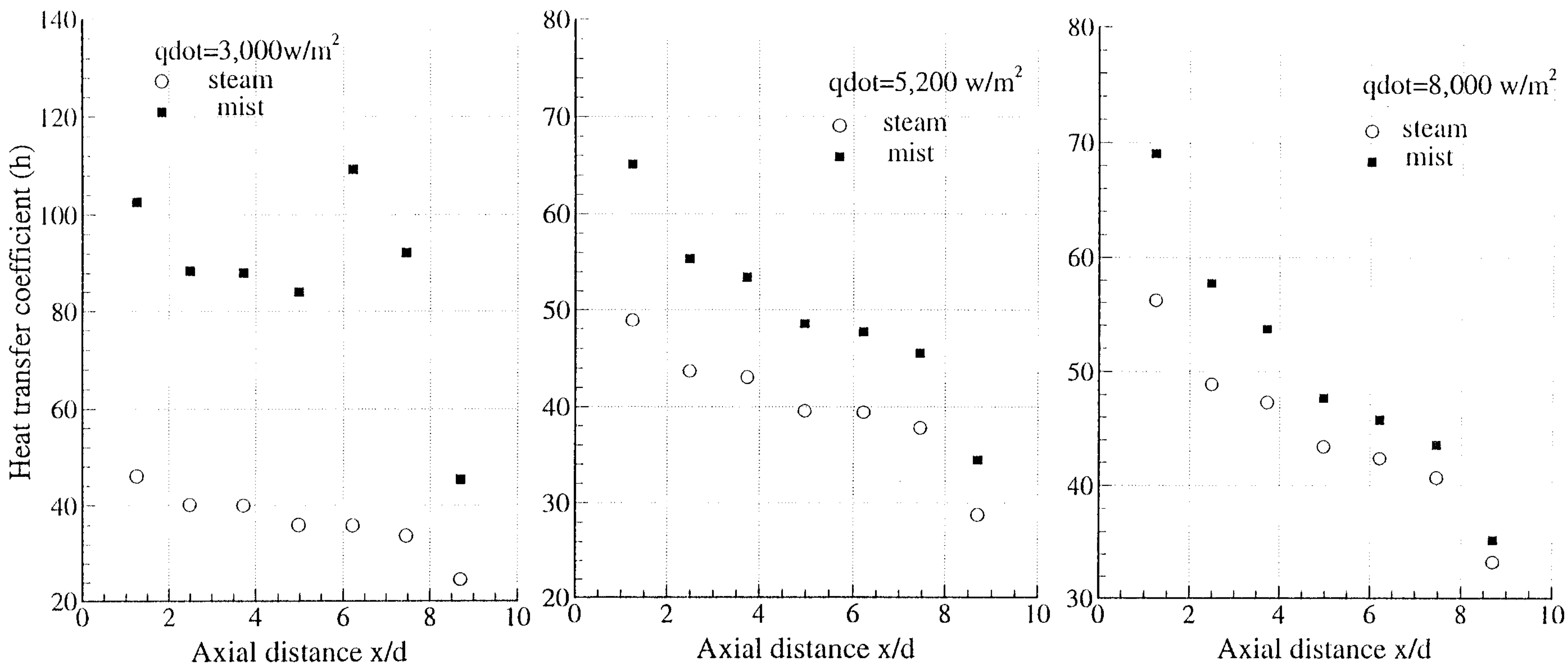
Droplet arithmetic mean diameter: d_{10} = 9 microns



Comparison of heat transfer coefficient for both mist flow and steam-only flow

Steam Renolds number: Re=10,000

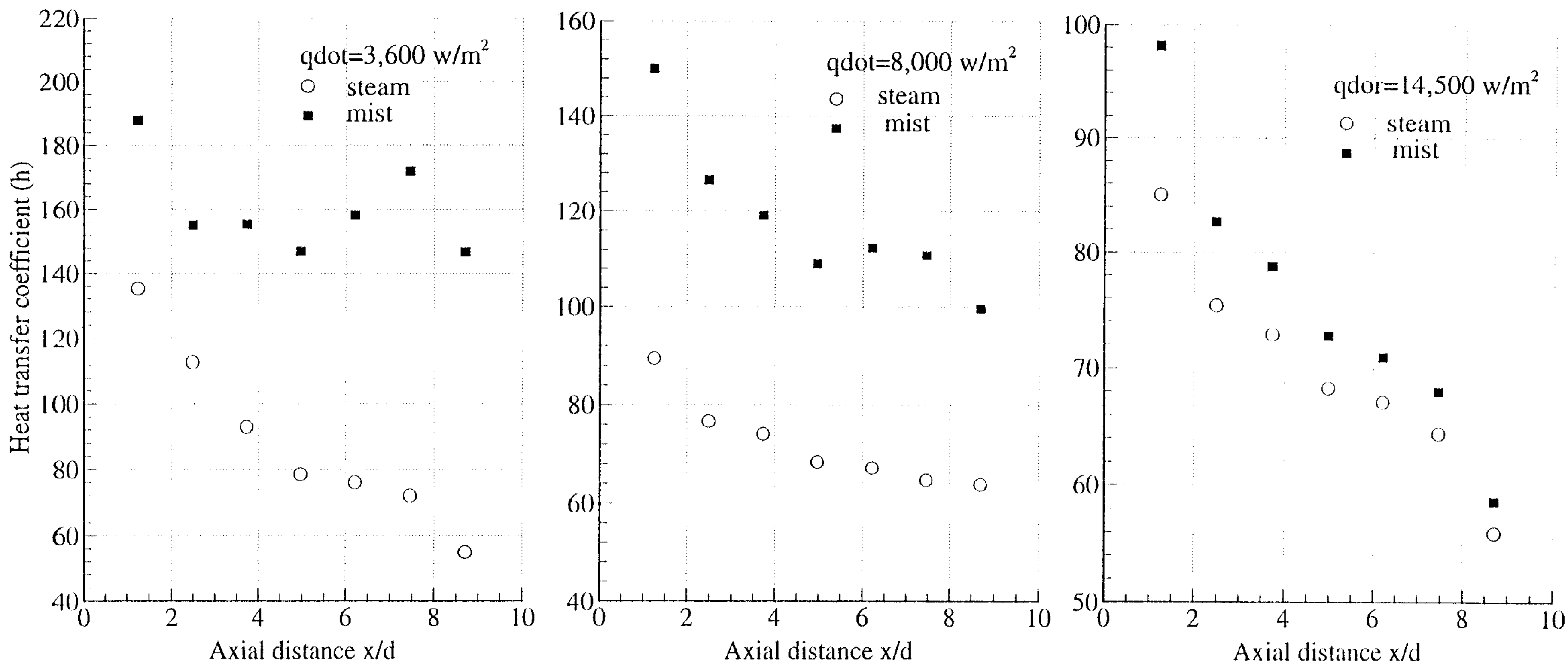
Droplet arithmatic mean diameter: 9 microns



Comparison of heat transfer coefficient for both mist flow and steam-only flow

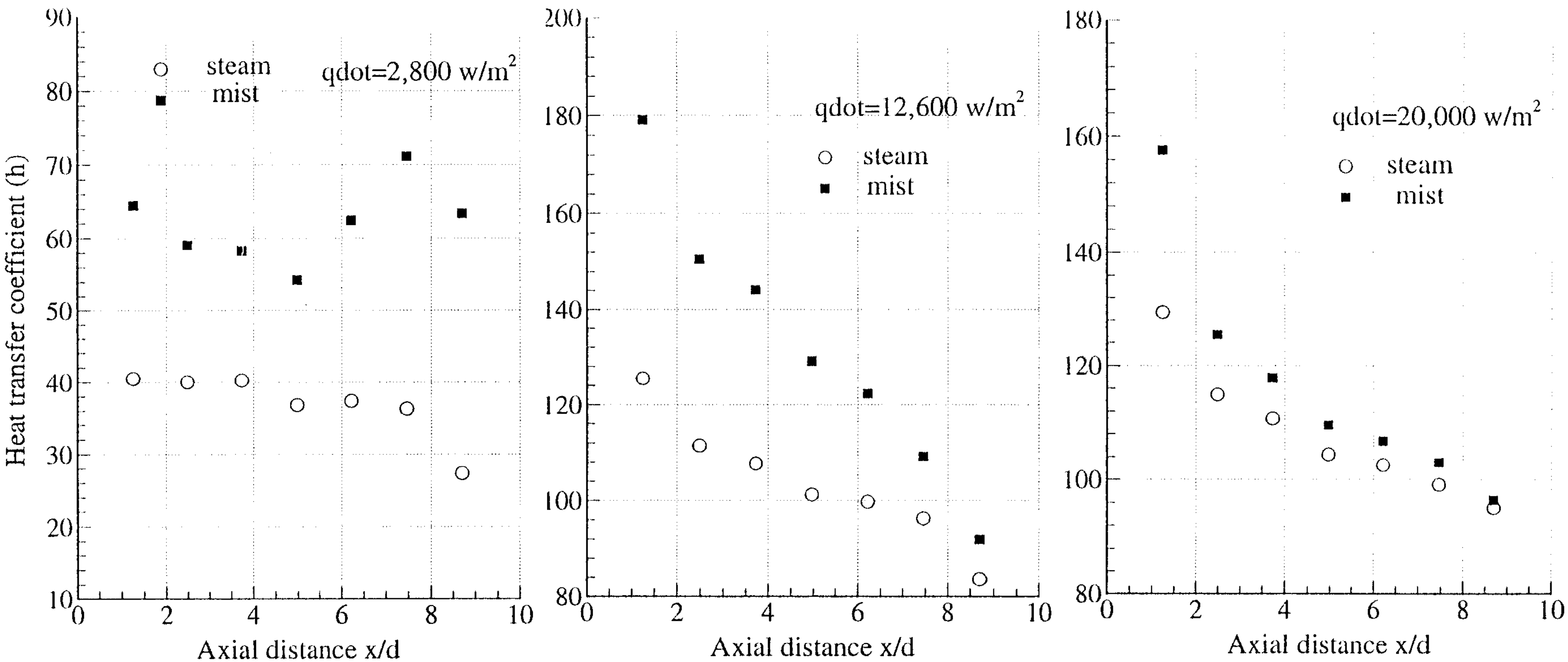
Steam Reynolds number: Re = 20,000

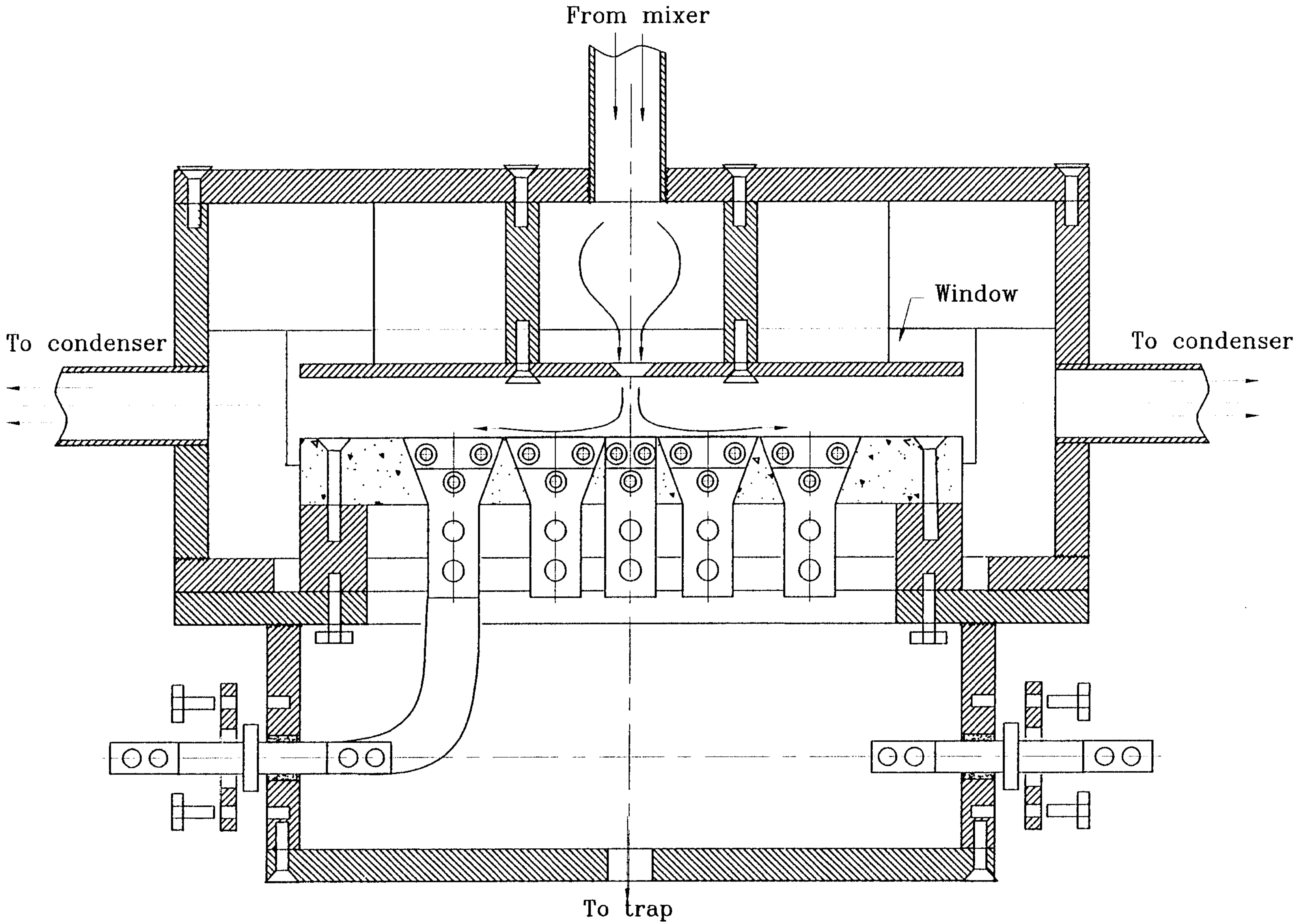
Droplet arithmetic mean diameter: 9 microns



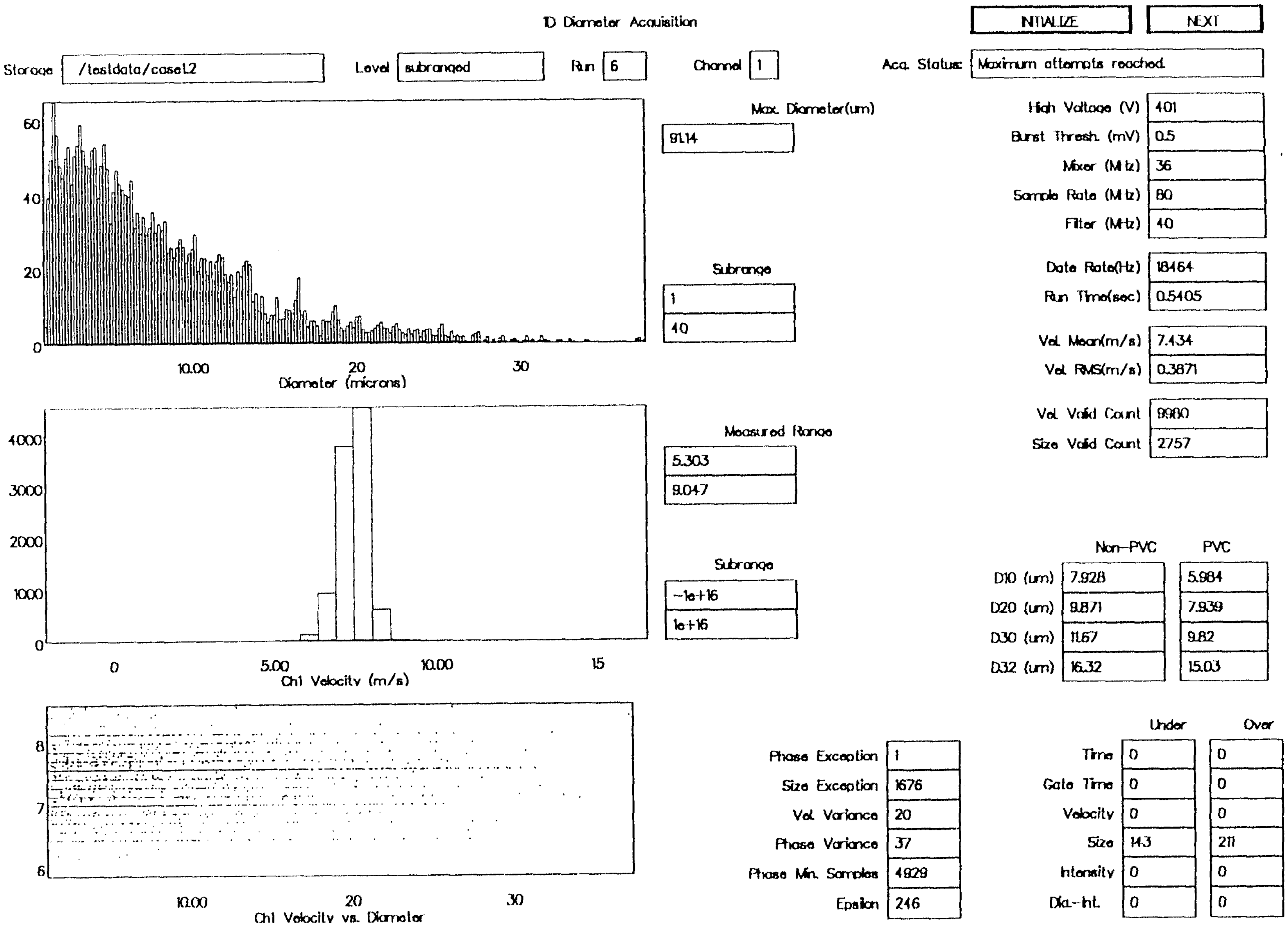
Comparison of heat transfer coefficient for both mist flow and steam-only flow

Steam Reynolds number: Re=35,000
Droplet arithmetic mean diameter: 9 microns

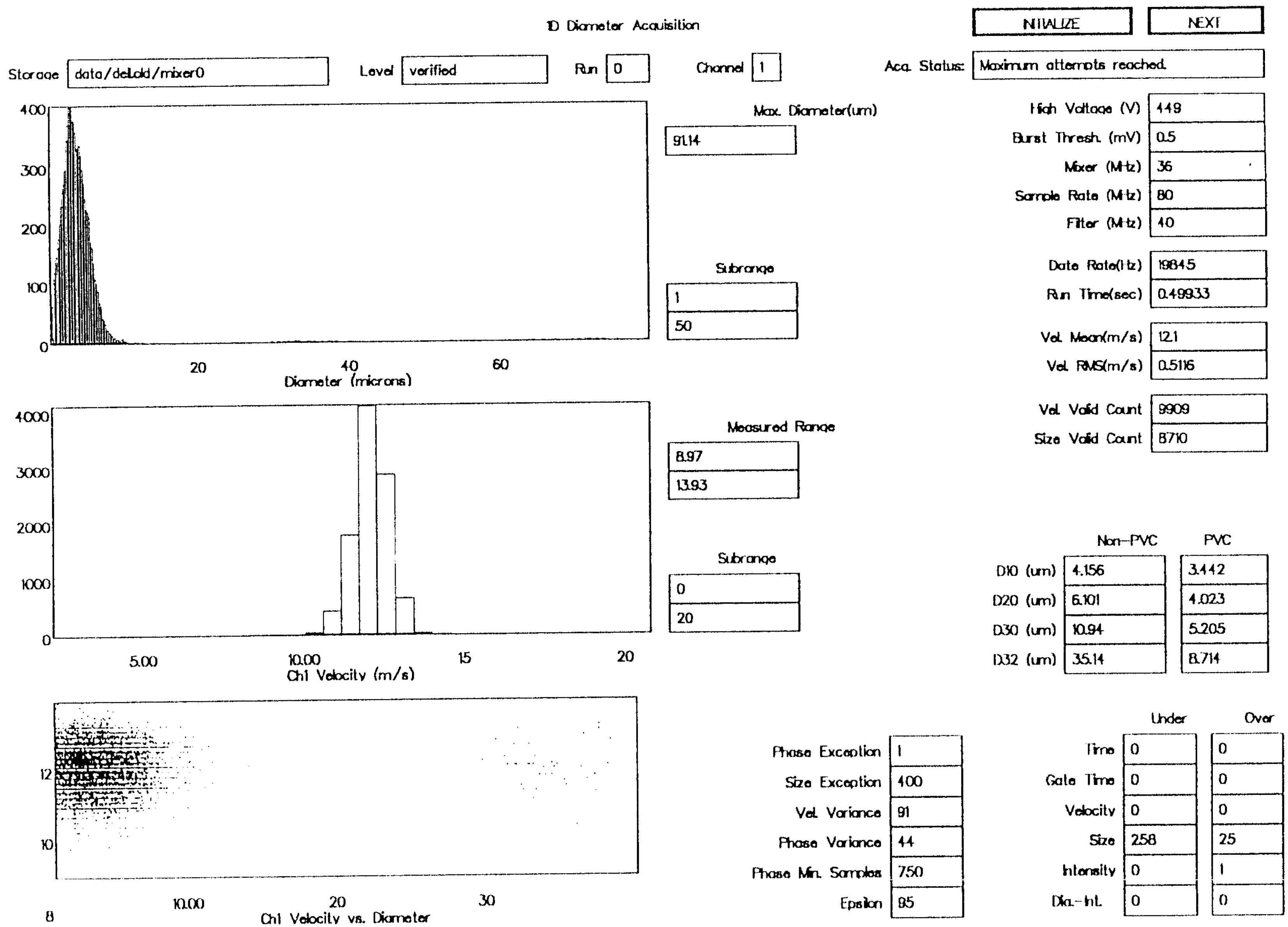




Test section layout for jet impingement with flat target



Typical droplet size distribution for atomizing system with pressure atomizers



Typical droplet size distribution for atomizing system with steam-assist atomizers