Applied Thermal Engineering 87 (2015) 106–116

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Pressure drop analysis of steam condensation in air-cooled circular tube bundles

Alan O'Donovan*, Ronan Grimes

Stokes Institute, Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Limerick, Ireland

HIGHLIGHTS

- Steam-side pressure losses in circular tube bundles are quantified.
- Magnitude of measured pressure losses are in the range of 130–250 Pa.
- Frictional losses are, largely, offset by momentum recovery in the condensing flow.
- A review of two-phase frictional pressure drop models/correlations is presented.
- Experimentally-derived frictional pressure drop is predicted best using the model of Lockhart & Martinelli.

ARTICLE INFO

Article history:
Received 25 February 2015
Accepted 28 April 2015
Available online 12 May 2015

Keywords:
Air-cooling
Condensation
Two-phase flow
Pressure drop

ABSTRACT

Pressure losses on the condensing-side of an air-cooled condenser (ACC) have the potential to inhibit condenser performance and, ultimately, curtail plant efficiency. However, little information is available on the magnitude and effect of these losses in an ACC under typical Rankine cycle operating conditions. This article seeks to improve current understanding on steam-side pressure losses in ACCs by presenting an experimental study on the losses in a full-scale ACC circular tube bundle. Saturated steam at low pressure was condensed by a cross flow of cooling air, provided by a bank of axial fans. Full condensation occurred in all measurements, which were carried-out over a steam pressure and temperature range of approximately 0.05–0.14 bar absolute and 33–55 °C, respectively. These test parameters ensured that measurement program test conditions were representative of those expected in an operational thermoelectric power plant. Experimental mass fluxes, per individual tube, varied from 0.7 to 2 kg/m^2 s during testing. The pressure drop characteristics were, therefore, analysed over a vapour Reynolds numbers range of 1890–5150 and liquid Reynolds number range of 25–95. Results indicate that the measured pressure drop through the tube bundle was relatively small, in the range of 130–250 Pa. As shown in this article, the reason for this was due to momentum recovery as the steam condenses to form liquid condensate. This phenomenon offsets the frictional losses, which are shown to be comparable in magnitude to momentum recovery in a condensing flow. However, this may not always be the case. Therefore, since the frictional component is traditionally the most problematic to predict, a range of liquid–gas two-phase frictional pressure drop predictive models were reviewed, and are presented herein. Comparisons between these models and the experimental data show that the most applicable model was found to be that of Lockhart & Martinelli. This demonstrated reasonable accuracy of ±18%.

1. Introduction

Wide-scale deployment of alternative energy technologies such as Concentrated Solar Power (CSP) will be dependent on the development of enhanced air-cooling strategies for use in the plant's Rankine cycle. The current industry standard for air-cooling is the A-frame Air-Cooled Condenser (ACC). This has been shown to suffer from significant design flaws manifested by non-uniform air flow [1,2], steam-flow maldistribution [3], susceptibility to inclement weather conditions [4–6], and backflow [7–9]. The net result of these deficiencies is a reduction in condenser effectiveness and performance. Ultimately, plant losses are incurred which

---

* Corresponding author.
E-mail address: alan.odonovan@ul.ie (A. O'Donovan).

http://dx.doi.org/10.1016/j.applthermaleng.2015.04.072
1359-4311/

Nomenclature

A	cross sectional area, m^2
C	separated flow regime constant
D	tube diameter, m
d_e	tube external diameter, m
d_f	fin diameter, m
dL	incremental length, m
dp/dz	pressure gradient, Pa/m
Fr	Froude number
f	friction factor
G	mass flux (mass velocity), kg/m^2 s
g	gravitational acceleration, m/s^2
h	head height, m
L	tube length, m
$\dot{m}$	mass flow rate, kg/s
N_r	number of condenser rows
N_t	number of condenser tubes
P	Pressure, Pa
$\overline{P}$	Mean pressure, Pa
Re	Reynolds number
We	Weber number
X	Martinelli parameter
x	Steam quality

Acronyms

ACC	air-cooled condenser
CSP	concentrated solar power
MACC	modular air-cooled condenser

Greek symbols

α	void fraction
ΔP	pressure change, Pa
Δz	distance between inlet & outlet pressure transducers, m
θ	condenser inclination angle, radian
μ	viscosity, kg/ms
ρ	density, kg/m^3
σ	surface tension, N/m
ϕ	two-phase multiplier
ω	uncertainty

Subscripts

avg	average
e	exit
Fr	based on Froude number
frict	friction
gd	Grönnerud
h	homogeneous
i	inlet
L	liquid
Lo	liquid-only
meas	measured
mom	momentum
st	static
V	vapour
Vo	vapour-only

reduce the viability of the plant as a competitor to fossil-fuel power. Current ACCs are, thus, non-conducive to CSP plants achieving parity with traditional thermoelectric power plants. In order to alleviate deficiencies associated with current ACCs, a modular air-cooled condenser (MACC) is proposed. It has been shown through previous studies by O'Donovan and Grimes [10], Moore et al. [11] and Butler and Grimes [12] that this design has the potential to maximise plant output and minimise parasitic losses. However, a factor which could inhibit the performance of the MACC, or any ACC for that matter, is the pressure losses associated with the two-phase condensing flow of steam through the tube bundle. Studies addressing this issue are not well-documented in the current literature.

Condensation of steam constitutes a two-phase flow as a liquid and vapour phase are in simultaneous motion inside a pipe. Steam commonly enters a pipe as a single-phase vapour and, as the latent heat of vaporization is rejected to the cooling medium, liquid condensate forms to establish a two-phase flow. The condensing flow experiences hydrodynamic losses due to a combination of frictional, momentum, and gravitational effects through the condenser tube. Excessive pressure drop on the condensing-side will reduce the generating capacity of a given plant by increasing the steam turbine back-pressure. Therefore, in the design and testing of condensers, large condensing-side pressure losses should be avoided. According to Palen et al. [13], such losses should be small relative to the steam turbine outlet pressure and, in general, should not be greater than 10–15% of the operating pressure.

To ensure that pressure losses are within an acceptable limit, measurements have been taken on a full-scale MACC prototype under vacuum conditions – deemed to be representative of typical operating conditions. The MACC prototype essentially consists of a compact heat exchanger tube bundle coupled to a bank of axial fans. The tube bundle comprises of a staggered bank of annularly-finned round tubes, through which flows steam. Air flow, to which the heat is transferred, is provided by the axial fans and flows in a direction transverse to the steam. Pressure drop data was collected for a range of fan speeds (air flow rates) and steam flow rates, representative of the exit conditions of a 50 MW turbine. From a review of the literature, it appears that there is little-to-no information regarding pressure losses on the condensing-side in tube bundles or in full-scale ACCs. The majority of research concerns the flow losses on the air-side. A limited number of studies [14,15] examine the pressure losses in plate heat exchangers, but such geometries are markedly different to the one presented herein. Through experimental measurements, this paper seeks to improve understanding of flow losses associated with condensing flows of steam in circular tube bundles.

Despite the lack of literature addressing condensing flows of steam, there does appear to be a significant body of work focussing on the frictional component of two-phase pressure losses. Most of this work is based around the development of empirical correlations to predict the frictional pressure drop. Some of the most prominent, and widely-cited, correlations include Lockhart and Martinelli [16], Grönnerud [17], Friedel [18], and Müller-Steinhagen and Heck [19]. However, the very nature of their empiricism means that the correlations are limited by the range of their underlying database, notwithstanding the accuracy within that same database. As such, a number of studies have been carried-out to ascertain the applicability of such correlations to particular conditions. Through comparison with pressure drop measurements, Idsinga et al. [20] assessed the applicability of eighteen correlations for adiabatic steam-water flows at mass fluxes in the range of 270–4340 kg/m^2 s.