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Performance characteristics of artificial coatings applied to steam surface condensers

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ABSTRACT

Recent developments in artificial protective coatings (APCs) and their application techniques have made it possible to consistently apply uniformly thin coatings. However, documented testing procedures are limited, which specifically deal with the thermal performance of these coatings. Moreover, recently developed coatings and application techniques are unique in many aspects and there exists the need to test their combined performance. There are also insufficient industrial guidelines to regulate the selection and application of these coatings. This paper investigates the measurement of the thermal performance of these coatings applied to new brass tubes. The double-pipe counter-flow heat exchanger, that was designed, manufactured and commissioned, is described. Heated water is used to simulate condensing steam, thus enforcing repeatable convection coefficients that are similar in magnitude to condensing steam. The measured annular convection coefficients (tested on new uncoated tubes) indicate the heat exchanger achieves fully-developed hydrodynamic conditions, and the measured Nusselt numbers agree within up to ±5% of literature correlations. Three different coatings are tested, with thicknesses ranging from 40 μm to 130 μm. Thermal performance is measured in terms of the coating thermal conductivity, the effective coated-tube conductivity, and the coating factor. Additionally, the pressure drop measurements agree within ±5% of smooth tube predictions. The Heat Exchange Institute (HEI) method for determining the heat transfer rate of steam surface condensers (Heat Exchange Institute, Standards for Steam Surface Condensers, Heat Exchange Institute (HEI), Cleveland, Ohio, 2012, 11th edition) makes no provision for APCs. However, this paper shows how to modify the design cleanliness factor or the material correction factor to account for APCs. Single tube tests are related to the overall condenser performance, and hence are used to show how coating guidelines may be determined in terms of the coating conductivity and thickness.

1. Introduction

Vacuum steam surface condenser tubes suffer from fouling, erosion, and corrosion. These degradation mechanisms not only cause an increase in thermal resistance, but most importantly they result in premature tube failures. Artificial protective coatings (APCs) are used to mitigate these mechanisms, and have been shown to be an effective countermeasure against corrosion and erosion [2], and hence an alternative to tube replacement [3,4]. Recent application techniques and the coatings themselves have seen significant advances. This paper addresses the question of quantifying the thermal performance of these coatings.

Despite cooling water treatment, condenser tubes still fall victim to fouling, erosion, and corrosion. Fouling may be categorized into two main types: macro fouling and micro fouling. According to Tsou [5], micro fouling may refer to: corrosion, scaling, particulate fouling, and biological fouling. Macro fouling encompasses the restriction of flow through the tubes, by foreign materials such as organic matter and inorganic debris. Fouling shall refer solely to micro fouling in this paper.

Erosion removes the passive oxide layer as well as tube parent material, and is caused by large levels of suspended solids and high local cooling-water velocities. Erosion normally occurs where the flow pattern changes, i.e. at the entrance or exit of the tube [6]. Such situations also result in what is termed inlet-end erosion/corrosion [7].

General corrosion acts on the entire tube and causes material loss along the length of the tube. However, accelerated forms of corrosion preferentially attack concentrated areas of the tube. Examples include pitting corrosion (an accelerated corrosion process

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Nomenclature

Symbols

A	area (m^2)
b	systematic standard uncertainty (W/m K)
d	diameter (m)
h	convection coefficient (W/m^2 K)
J	total number of variables in DRE
k	thermal conductivity (W/m K)
L	length (m)
m	mass flow rate (kg/s)
Q	heat transfer rate (W)
R	thermal resistance (K/W)
s	random standard uncertainty (W/m K)
t	thickness (m)
T	average/bulk temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
v	velocity (time averaged) (m/s)
V	volumetric flow rate (m^3/s)
X	arbitrary variable
f_D	friction factor (Darcy)
F_C	cleanliness factor
F_M	HEI material correction factor
F_M^+	coated material correction factor
F_W	HEI inlet water temperature correction factor
ΔT_{lm}	log mean temperature difference (K)
$\Delta\overline{T}$	averaged mean temperature difference (K)

Greek letters

μ	absolute viscosity (kg/s.m)
ρ	density (kg/m^3)

Subscripts

ann	annulus
c	cold or coating
e	equivalent or hydraulic
eff	effective
f	fluid
h	hot or convection
i	inlet or inner
m	mean
o	outlet or outer
w	wall

Dimensionless groups

Nu	Nusselt number, hd/k
Pr	Prandtl number, $\mu c_p/k$
Re	Reynolds number, $\rho vd/\mu$

Acronyms

APC	artificial protective coating
BWG	Birmingham wire gage
DRE	data reduction equation
RTD	resistance temperature detector
TSM	Taylor series method
UMF	uncertainty magnification factor

occurring in passive metals at defects in the passive layer [8]) and crevice corrosion (corrosion occurring at a crevice or under a crevice or deposit [8]). These corrosion mechanisms become autocatalytic as the pH and concentration of ions concentrate in the pit or under the crevice and conditions worsen leading to accelerated corrosion. This rapidly leads to tube leaks and hence premature failure well before their expected lifespan. This has critical ramifications because any tube leaks result in contamination of the boiler feed water.

APCs form an inert barrier of protection between the tube parent material and the cooling water. Fig. 1 shows the relative thickness of these coatings as well as the preferential filling of a pit in the tube wall.

Other mitigation techniques include tube liners and retubing. However, Putman [10] cites tests which show that tube liners can result in heat transfer penalties of up to 30% as a result of air gaps formed between the liner and tube. Furthermore, although retubing is generally opted for, it is not always feasible. For example,

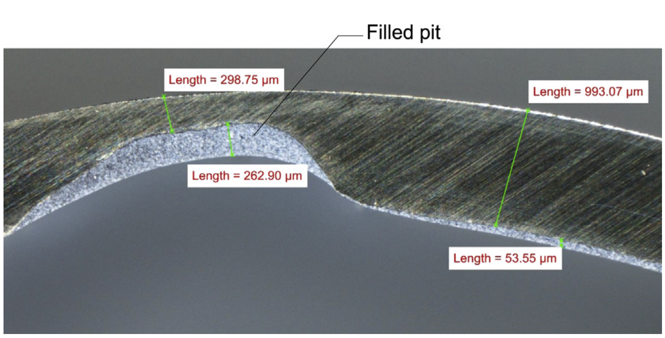

Fig. 1. Micro-graph of preferential filling of pit by coating [9].

many stations can neither afford to leave the unit off-line for the typical retubing period (approximately three months depending on the condenser size), nor do they have the budget. Furthermore, lead times of new tubing can be as along as two years from the supplier. In these situations, APCs can be used as an interim measure until an opportunity to retube becomes available.

Before implementing APCs their thermal performance needs to be quantified so that the effect on the overall condenser performance can be predicted. This allows coating specifications to be formulated to control the selection and application of these coatings. Additionally, the optimum point when the coating should be applied in the condenser life-cycle can be determined.

Some of the earliest published thermal performance testing of APCs was conducted by Sato and Nagata [11], who considered epoxy and polyester resins. They specified maximum coating thicknesses of 7 μm for epoxy and 22 μm for polyester to achieve satisfactory thermal performance. These standards were specified in terms of a coating resistance (analogous to fouling resistance) equal to 2.6×10^{-5} m^2 K/W and did not explicitly describe the coating conductivity. Furthermore, it is questionable whether such thin coatings were continuous through the length of the tube, and no methods of measuring or verifying this were given.

Mussalli [7] considered a larger range of APFs consisting of: epoxies, poly-esters, phenolics and a fluorinated urethane. Field tests concluded a reduction in corrosion and fouling as a result of applying an APC which caused an overall increase in performance [7]. However, the thermal performance results were reported in terms of a pseudo cleanliness factor (ranging from 0.5 to 0.97 depending on the coating) and the estimated coating resistance (based upon an average overall heat transfer coefficient).

In the HEI's "Standards for Steam Surface Condensers" [1], no explicit provision is made for APCs. The traditional approach is to include an effective cleanliness factor of the coatings [4,7,12].