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B. Brajuskovic, D. Capatina, J. Collins, P. Den Hartog and J. Reneker

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Contributed paper

Subcooled critical heat flux: an assessment of the risk to front-end and beamline components of synchrotron light sources

B. BRAJUSKOVIC[1]†, D. CAPATINA[1], J. COLLINS[1], P. DEN HARTOG[1] AND J. RENEKER[2]

[1]Argonne National Laboratory, Advanced Photon Source, AES Division, 9700 S. Cass Ave., Argonne. IL 60439-4800, USA

[2]Sandia National Laboratories, Pulsed Power Sciences Center, 1515 Eubank Blvd. SE, Albuquerque, NM 87185, USA

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X-ray absorbers in the front ends and beamlines of synchrotron light sources are exposed to very high thermal loads. Many facilities, such as the Advanced Photon Source, are investigating upgrades that will further increase the thermal load. The likelihood of exceeding the limit of subcooled critical heat flux (CHF) in these components was examined. The assessment was performed for both currently possible off-normal operational conditions, such as might occur in the event of a failure of multiple safety interlocks, and the anticipated operating conditions that may result from future upgrades. The subcooled CHF values were calculated using empirical equations frequently cited in the literature and then compared with the computed values of the heat flux at the walls of the component cooling channels in cases where the cooling wall temperature exceeded the water saturation temperature at local hydraulic conditions. Having in mind that the great majority of the available empirical correlations were developed for the conditions characteristic for the operation of heat exchangers in the nuclear power industry, the limitations of this approach are discussed and an experimental study of the subcooled CHF values in the conditions similar to those expected in the front-end and beamline components is proposed.

1. Introduction

Critical heat flux (CHF) is a phenomenon that manifests in sudden and severe drop in heat transfer efficiency. Once the heat flux reaches its critical level, a small further increase of heat flux leads to very large and instant increase in the temperature of the heat exchanger walls that can cause catastrophic material failure known as burn-out. The CHF phenomenon is caused by the sudden creation of a thin layer of vapour that separates cooling walls of cooling channels from the bulk liquid. Thus, CHF can occur only in those heat exchangers that are

† Email address for correspondence: bran@aps.anl.gov

characterized with both phase change and very high wall-to-coolant heat flux values. Typical systems where CHF can occur are the heat exchangers of nuclear power plants, and the nuclear power industry has invested remarkable resources into the investigation of CHF. Regrettably, a general correlation that would accurately predict the occurrence of CHF for a broad variety of geometries and operating conditions of heat exchangers is yet to be found. Lately, research has shifted to investigating the correlations optimized for the conditions of particular interest. A detailed report on the effort devoted to understanding and predicting CHF can be found in the work of Hall & Mudawar (2000*a*, *b*).

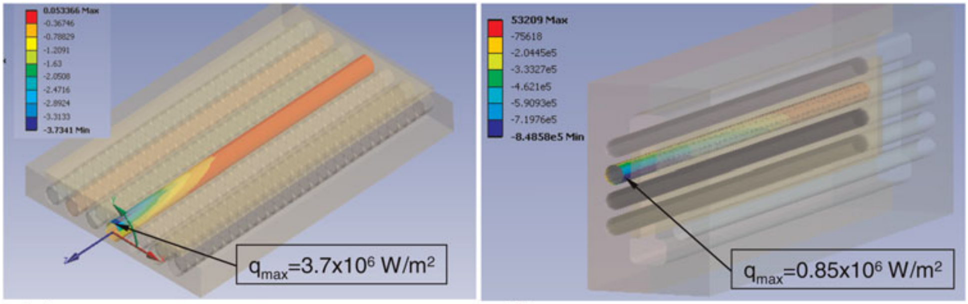
Until recently, subcooled CHF was not considered as one of the possible causes of catastrophic failures of front-end and beamline components at the Advanced Photon Source (APS), as these components were designed to eliminate the possibility of phase change by keeping the cooling channel walls below the saturation temperature. However, with recent user requests to have the ability to change the gap of their dual undulators during operation, it became apparent that the cooling channel walls of photon shutters could exceed the saturation temperature under off-normal operating conditions.

2. Comparison of computed wall-to-coolant heat fluxes with predicted subcooled CHF values

Once it became apparent that the phase change of the coolant could occur, cooling wall temperatures $T_{\rm w}$ and wall-to-coolant heat fluxes $q_{\rm w}$ were computed for photon shutters versions 1.2 and 2.0. It was assumed that shutters are exposed to the beam created by two inline undulator A units operating in off-normal conditions. Computations were made for 11 mm gap and 100 mA current for version 1.2 shutters and for 10.5 mm gap and 130 mA current for version 2.0 shutters. The subcooled CHF values used in comparison were obtained using Hall–Mudawar inlet conditions correlation (Hall & Mudawar 2000*b*), and the CHF look-up table created by Groeneveld *et al.* (2007), and then corrected to account for non-uniformly heated horizontal flow and the presence of coil inserts (Brajuskovic). Computed values of $T_{\rm w}$, $q_{\rm w}$ and predicted CHF values are given in Table 1. Preliminary results of the computations of temperatures and heat fluxes for version

Undulator parameters	Shutter version	Coolant flow (gpm)	$T_{\rm w}$ (°C)	$q_{\rm w}$ (MW m^{-2})	CHF Hall–Mudawar (MW m^{-2})	CHF look-up table (MW m^{-2})
Two undulator A units, 100 mA, 11 mm gap	1.2	0.5	285	3.1	2.7	5.5
		1.0	250	3.7	6.3	9.1
Two undulator A units, 130 mA, 10.5 mm gap	2.0	0.5	93	0.66	2.7	5.5
		1.0	75	0.85	6.3	9.1
Three undulator A units, 200 mA, 10.5 mm gap	2.0	0.5	182	1.53	2.7	5.5
		1.0	140	1.98	6.3	9.1

TABLE 1. Comparison of computed wall-to-coolant heat fluxes with predicted CHF values.



(*a*) *Version 1.2 (horizontal intercepting surface)* (*b*) *Version 2.0 (vertical intercepting surface)*

FIGURE 1. Computed q_w values: (*a*) version 1.2 (horizontal intercepting surface) and (*b*) version 2.0 (vertical intercepting surface).

2.0 shutters exposed to the most extreme beams expected after the APS upgrade are also included in Table 1. Computed q_w values are also given in figure 1.

3. Discussion

These results indicate that, at the current state of the APS, an occurrence of CHF represents a realistic risk only if version 1.2 shutters are exposed to the beam from two undulator A units operating at the most extreme conditions and component coolant flow is at its allowed minimum (0.5 gpm). This and a q_w-to-CHF ratio less than 2 computed for nominal coolant flow (1 gpm) resulted in two immediate recommendations: to increase the minimum coolant flow to 1 gpm and to maintain existing procedures in undulator gap changes for sectors with two inline undulators and version 1.2 shutters. Also, the replacement of all version 1.2 front-end components is recommended for the coming APS upgrade.

High q_w-to-CHF ratios computed for version 2.0 shutters indicate that CHF is an unlikely cause of their failure in the present even under the extreme conditions.

Preliminary results obtained for the extreme operating conditions expected after the APS upgrade indicate that CHF will not be the likely cause of failure for version 2.0 front-end components. However, more work is needed to study the effect of missteering and eventual design changes due to the other limiting factors before an accurate assessment is made. If further work indicates lower q_w-to-CHF than computed at present, more accurate correlations for CHF prediction will be required, and an experimental programme to obtain the correlations optimized for the conditions specific for front-end and beamline components will be proposed.

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