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# CMFD and the critical-heat-flux grand challenge in nuclear thermal–hydraulics – A letter to the Editor of this special issue

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The topic of this paper is particularly suited for celebrating Geoff Hewitt's 80th anniversary as he and his collaborators made numerous direct or indirect seminal contributions in this area. More generally, Geoff made an enormous number of contributions during his long and extremely productive career to the multiphase-flow and heat transfer area and one finds his impact on so many facets of this field. His writings, books, handbooks, publications, etc. are conspicuously present everywhere. In spite of his great achievements that resulted in so many honours from learned societies, Goeff remains such a humble scientist, never boasting about his work and well aware and eager to speak about the limitations of the current state of the art. I had the special privilege of knowing Geoff for some forty years now and collaborating sometimes closely with him. He is treated as the senior, respected and trusted person whenever he is present, while at the same time he is offering his friendship to the persons, young and old, surrounding him. Although he is supposed to have retired some fifteen years ago, he keeps teaching (well above the call of duty, because he loves it), lecturing and researching, acting as "a young assistant professor seeking tenure". Dear Geoff, I wish you a very Happy Birthday and hope you never stop acting like this.

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ABSTRACT

After very many rather naïve attempts to understand and model Critical Heat Flux (CHF) on the basis of unique mechanisms that resulted in a myriad models and of correlations, we came "back" to Look Up Tables that implicitly recognize that the data are not correlatable in general ways and then, with the advent of Computational Multi-Fluid Dynamics (CMFD) methods back again to predicting CHF mechanistically. The situation is clearly much more complicated in the fuel rod bundle assemblies used in nuclear reactors than in tubes or other simple channel geometries. For rod bundles, subchannel analysis methods have been used but the challenge of correlating CHF to the local conditions remains, in addition to the difficulties in computing the inter-subchannel fluxes.

Recently, CMFD computations of the critical heat flux became the grand challenge and efforts were undertaken on both sides of the Atlantic to produce predictions of CHF for both the Departure from Nucleate Boiling (DNB) and the Dryout situations in PWRs and BWRs, respectively. CMFD methods come closer to tackling in a "natural" way the fuel-bundle and transient problems also, as the same basic, microscopic-level models and numerical techniques can be applied to any geometry also under transient conditions if sufficient computational resources are available. Much more advanced instrumentation is in the meantime producing the much more detailed, microscopic data needed to validate the CMFD methods.

The paper reviews briefly the historical developments and then focuses on the recent CMFD work, its promises and still existing restrictions; the phenomena are too complex to be fully resolved by CMFD. Although we had set this as a goal over ten years ago, we are not there yet, but the spinoffs from this effort have been beneficial.



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## Introduction

In this paper, I am attempting to summarize the history and state of the art in Critical Heat Flux (CHF) for nuclear, thermal–hydraulic applications and the experiences gained in attempting to apply Computational Multiphase Fluid Dynamics (CMFD) methods to the problem. My experiences the last decade come from the interactions with the international communities that have attempted this, mainly the research community around the European projects NURESIM–NURISP–NURESAFE (NURESAFE, 2014) with which I have been closely associated. I use the "we" when I am referring to the work of these communities, rather than my own personal work.

The CHF phenomenon became a centre of attention with the development of the Light Water Reactor (LWR) technology in the fifties. Many papers dealing with CHF were published in the following decades, including several by G.F. Hewitt, whom this special issue of the journal is honouring (Hewitt, 1970, 1982; Hewitt and Hall-Taylor, 1970; Bennett et al., 1965, 1966, 1967; Ahmad et al., 2013, etc.). My choice of this topic seems to be quite appropriate for the occasion. G.F. Hewitt has a long-standing interest in it; the topic has a matching long history that I tried to review in a recent publication (Yadigaroglu, 2013) where I classified it as an "eternal" problem that "does not go away".

We can start by recalling briefly the basic facts: in nuclear thermal–hydraulics applications, CHF is basically the inability of the wall to evacuate the heat flux imposed to it (the case of a nuclear fuel rod), resulting in overheating of the wall (the fuel rod cladding) at high heat flux; under normal flow conditions[1] there are basically two broad categories of CHF. Departure from Nucleate Boiling (DNB) takes place at low-quality, under typically nucleate-boiling and bubbly-flow conditions by some kind of overcrowding of the bubbles or starvation from liquid of the wall. In the case of Dryout that is expected under high-quality, annular-flow conditions, depletion or *drying out* of the liquid film on the wall produces the CHF condition (Tong and Hewitt, 1972). Clearly one would expect intermediate cases; the phenomena are very complex and the details of the CHF mechanisms very diverse. Understandably, a full description and modelling of CHF (under all possible situations) is still not available after over half-a-century of efforts and may never become available; CHF is one of the "eternal" problems. Significant numbers of CHF papers continue to be published. The emphasis, the approach and the applications (e.g., CHF under thermodynamically supercritical conditions) have changed, but the problem remains and defies *the* solution. Although there is usually sufficient data from full-bundle experiments to satisfy the design and safety cases for nuclear reactors, the fuel vendors still rely on large-scale expensive testing to produce these data.

This paper summarizes first the historical developments in the CHF area to put in perspective the most recent results based on CMFD methods. The industrial challenge regarding CHF is to accurately predict the CHF condition in LWR fuel bundles. CHF is essentially governing the performance of the fuel and of the reactor core under normal operating conditions. Some or all the difficulties of the classical CHF prediction methods for fuel bundles that we will briefly recall below – correlations and/or subchannel analysis – would have been eliminated by CMFD simulations of the flow in a reactor fuel element bundle and simultaneous prediction of the CHF condition mechanistically. This was indeed one of the aims of the European NURESIM project launched in 2003 and followed by its successor NURISP and NURESAFE projects (NURESAFE, 2014). Prediction of CHF by CMFD methods could have been considered ten years ago as the Holy Grail, "a trip to the moon": even if success was not guaranteed, the effort would have produced significant spinoffs. The Apollo program has landed a man on the moon in nine years, eleven years from the creation of NASA in 1958. A lot of progress has been made towards CMFD predictions of CHF since the launching of NURESIM, in Europe but also worldwide with similar projects, such as the CASL (2014) project in the US, but we have not reached the CHF goal yet...

### CFD and CMFD

Computational Fluid Dynamics (CFD) has existed for a few decades now but had not been used extensively in reactor technology, in particular for safety cases. CMFD is more recent (Yadigaroglu, 2003), and it is only in the last couple of decades that its promise and potential application to reactor systems became visible. CFD and CMFD promise to solve some problems that have resisted full understanding and modelling for a long time, like the prediction of the CHF in LWRs and the detailed prediction of coolant velocity, temperature and void-fraction distributions in rod bundles (the *subchannel analysis* problem), but we are not quite there yet.

Although steady-state CHF has been studied very extensively, much less is known about the occurrence of CHF under transient conditions, a situation that is, however, of great importance in nuclear reactors, e.g., under LOCA conditions or during transients. For CHF and subchannel analysis, the particular difficulty on how to predict these under *transient* conditions is similar to the much simpler one of prediction of heat transfer from wall to coolant under transient flow conditions. In both cases all the correlations and other closure laws upon which the solutions are based are in principle applicable only to steady states. The outcomes certainly depend on the very nature of the transient and cannot be generically described, and even less, correlated. All system codes use the quasi-steady-state assumption for all closure laws (i.e., the correlations are evaluated based on the instantaneous values of their parameters, ignoring any transient effects) and in particular for CHF. Pasamehmetoglu and coworkers (Pasamehmetoglu and Gunnerson, 1985; Pasamehmetoglu et al., 1987) present a couple of rare analyses of the transient CHF problem. The CFD and CMFD methods by their own nature are based on more basic notions like turbulence and transient conduction, although they still often make use of rather empirical closure laws (e.g., the laws describing the forces acting on bubbles). Therefore they are inherently not limited to steady states and should come much closer to treating properly the difficult transient situations.

As our review of the recent CMFD approaches to the CHF problem suggests, it is fairly clear that recent good progress in CMFD applications has been mainly made possible not so much by improvements in methods (that have existed for a long time) and of our understanding and modelling of the physical phenomena (that has not improved so much) but rather by the tremendous increase in computing power (that allows making the mesh size much smaller) but also by advances in instrumentation (electronics and information technology) that allows data collection now at the microscopic level needed for the CMFD validations (Yadigaroglu, 2013). The concept of multi-scale computations covering length scales from the microscopic to the system scale (Yadigaroglu, 2005) applies also by analogy to the experimentation where experiments can be conducted now at the microscopic scale to provide data for the validation of micro-scale simulations and produce the closure laws needed for meso- and systems-scale computations.

## Historical development

Understandably, the first CHF experiments were conducted with uniformly heated tubes, as well as in other simple geometries

[1] We are not concerned here about other situations, like, e.g., CHF under practically stagnant flow conditions as they may take place during the blowdown of a reactor following a loss-of-coolant accident, or low-heat-flux, hydrodynamic Dryout or boil-off situations.