Critical Pressure of Non-Equilibrium Two-Phase Critical Flow

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Introduction

Critical pressure is defined as the pressure existing at the exit edge of the piping, when it remains constant despite a decrease in the back. According to this definition the critical pressure is larger than the back pressure and for two-phase conditions below saturation pressure. The two-phase critical pressure has a major influence on the two-phase critical flow characteristics. Therefore it is of high significance in calculations of critical mass flux and critical depressurization rate, which are important in the fields of Nuclear Reactor Safety and Industrial Safety.

At the Nuclear Reactor Safety field is useful for estimations of the Reactor Cooling System depressurization, the core coolant level, and the pressure build-up in the containment. In the Industrial Safety field it is helpful for estimating the leakage rate of toxic gases from liquefied gas pressure vessels, depressurization of pressure vessels, and explosion conditions due to liquefied gas release.

For physical description of non-equilibrium two-phase critical flow it would be convenient to divide the flow into two stages. The first stage is the flow of subcooled liquid at constant temperature and uniform pressure drop (i.e., the case of incompressible fluid and uniform piping cross section). The rapid flow of the liquid causes a delay in the boiling of the liquid, which begins to boil below saturation pressure, at thermal non-equilibrium. The boiling is the beginning of the second stage, characterized by a sharp increase of the pressure drop. The liquid temperature on the second stage is almost constant because most of the energy for vaporization is supplied from the large pressure drop.

The present work will focus on the two-phase critical pressure of water, since water serves as coolant in the vast majority of nuclear power reactors throughout the world.

The Influence of Water Temperature

A large amount of tests measuring two-phase critical mass fluxes and critical pressures have been described by Ilic et al (1986). The Reocreux (1974) tests deserve special attention. Reocreux classified his tests according to the critical pressure, as shown in Table 1. From Table 1 it is easy to diagnose correlation between the critical pressure and water temperature. Pressure curves of the four groups of tests with the same critical pressure of 1.75 bar are drawn in Figure 1. From here there does not seem to be any correlation between inlet pressure and critical pressure. An additional conclusion from Figure 1 is the independence of critical pressure from pipe geometry. Clearly the pressure drop, which is geometry dependent, does not influence the critical pressure. One can easily assume according to Figure 1 four pipes with different length, but with the same water temperature and the same inlet pressure, having the same critical pressures at their end.

Reocreux tests from # 400 to # 435 were found by Ilic et al (1986) as qualified database for the critical flow of water. More detailed observations of these tests appear in Table 2. It is obvious from this table that the main parameter governing critical pressure is water temperature. This conclusion matches the assumption of Burnell (1947) that the critical pressure depends on water stagnation temperature as expressed by the following empirical correlation:

$$P_{Crit} = P_{Sat}(1 - 5.366\sigma)$$

While the saturation pressure depends on water temperature and surface tension, σ is also a function of water temperature. The above conclusion is reinforced by the wide use of empirical curves of critical pressure ratio versus water saturation pressure in the valve industry. Due to these curves, the critical pressure of water depends only on water temperature. A typical example for such curve appears in "FISHER CONTROLS" handbook (1977).

Table 1: Critical pressure classification table according to Reocreux (1974).

Critical pressure [bar]	Test number	Critical mass flux [kg/(m²·s)]	Water temperature [°C]	Saturation pressure [bar]
1.5	403 - 404	4180	116.7	1.787
	400 - 402	6500	116.65	1.784
	405 - 407	8650	116.3	1.763
	408 - 411	10300	115.9	1.741
1.75	423 - 428	4360	121.75	2.098
	420 - 422	6500	121.1	2.055
	429 - 433	8500	121.0	2.049
	433 - 435	10100	120.85	2.040
2.0	446 - 450	4210	126.1	2.400
	440 - 445	6400	125.4	2.349
	451 - 454	8520	125.2	2.335
	455 - 459	10180	125.1	2.327

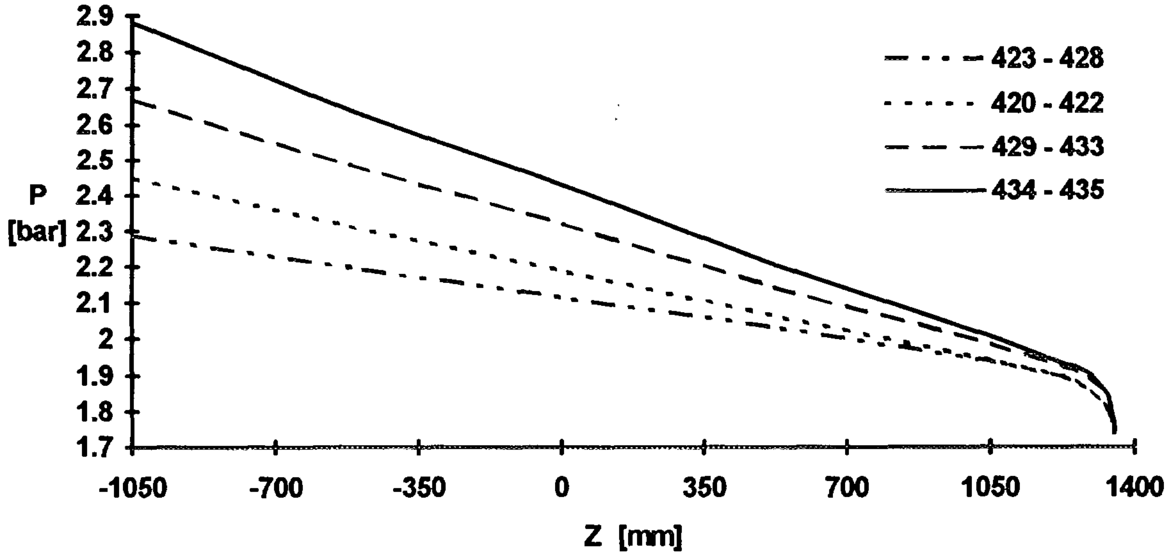

Figure 1: The pressure curves of tests 420 to 435 (Z coordinates are identical to Reocreux coordinates).

Table 2: Thermodynamics parameters of Reocreux qualified tests.

Test number	Inlet pressure [bar]	Critical mass flux [kg/(m²·s)]	Water temperature [°C]	Saturation pressure [bar]	Critical pressure [bar]	Critical void fraction
403 - 404	1.993	4180	116.7	1.787	1.506	0.55
400 - 402	2.181	6500	116.65	1.784	1.502	0.25
405 - 407	2.412	8650	116.3	1.763	1.501	0.12
408 - 411	2.630	10300	115.9	1.741	1.505	0.07
423 - 428	2.286	4360	121.75	2.098	1.755	0.57
420 - 422	2.449	6500	121.1	2.055	1.752	0.31
429 - 433	2.669	8500	121.0	2.049	1.752	0.20
433 - 435	2.877	10100	120.85	2.040	1.750	0.16

On Figure 2 the critical pressure ratio of some empirical databases qualified by Ilic et al. (1986) are shown as function of water temperature. Burnell and "FISHER" curves are also presented on this graph. It is clear from this graph that the "FISHER" empirical curve matches well the empirical results. Within the range of most practically important water temperatures, from 100 °C to 350 °C it is acceptable to limit the two-phase critical pressure by lower and upper bounds:

$$P_{Crit} = P_{Sat}(0.95 - T/1000)$$

$$P_{Crit} = P_{Sat}(1.1 - T/1000)$$

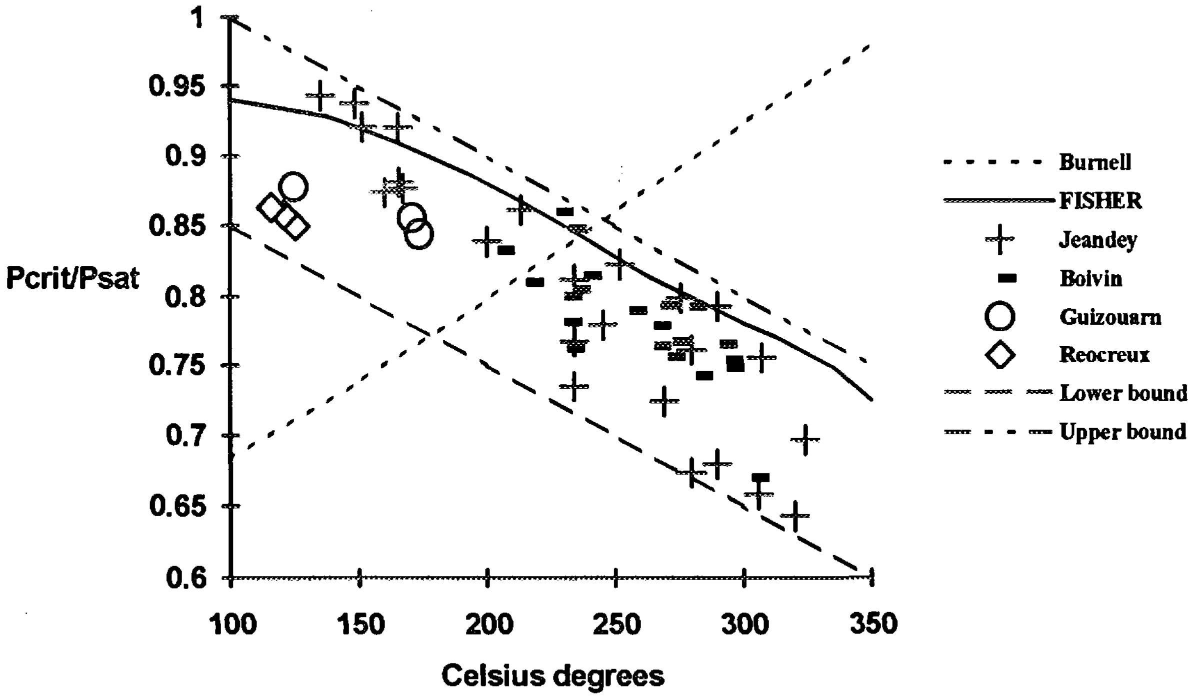

Figure 2: Critical pressure ratio versus water temperature.

Conclusions and Discussion

The main conclusion of this work is the existence of strong dependence of two-phase critical pressure on water temperature. There is no evidence of any significant influence of the inlet pressure or the geometrical conditions on the critical pressure. All of the above mentioned discussion points to the water temperature as the parameter that determines the two-phase critical pressure. Despite this conclusion an analytical relation between water temperature and critical pressure is not available. This analytical relation could be the aim of further research.

The range between the empirical bounds of critical pressure suggested in this work is narrower than the analytical range proposed by Minzer and Elias (1996). The new bounds may improve the two-phase critical mass flux predictions calculated by the bounding method proposed in that same paper.

Nomenclature

P - pressure [bar]
T - temperature [°C]
σ - surface tension [N/m]

Subscripts

Crit - critical
Sat - saturation

References

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