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Simulation of performance of centrifugal circulators with vaneless diffuser for GCR applications

N. Tauveron*, I. Dor

CEA, DEN, DER/SSTH, 17 rue des Martyrs, F-38054 Grenoble, France

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ABSTRACT

In the frame of the international forum GenIV, CEA has selected various innovative concepts of gas-cooled nuclear reactor. Thermal hydraulic performances are a key issue for the design. For transient conditions and decay heat removal situations, the thermal hydraulic performance must remain as high as possible. In this context, all the transient situations, the incidental and accidental scenarii must be evaluated by a validated system code able to correctly describe, in particular, the thermal hydraulics of the whole plant. As concepts use a helium compressor to maintain the flow in the core, a special emphasis must be laid on compressor modelling. Centrifugal circulators with a vaneless diffuser have significant properties in term of simplicity, cost, ability to operate over a wide range of conditions.

The objective of this paper is to present a dedicated description of centrifugal compressor, based on a one-dimensional approach. This type of model requires various correlations as input data. The present contribution consists in establishing and validating the numerical simulations (including different sets of correlations) by comparison with representative experimental data. The results obtained show a qualitatively correct behaviour of the model compared to open literature cases of the gas turbine aircraft community and helium circulators of high temperature gas reactors. The model is finally used in a depressurised transient simulation of a small power gas fast reactor (ALLEGRO concept). Advantages of this model versus first preliminary simulations are shown. Further work on modelling and validation are nevertheless needed to have a better confidence in the simulation predictions.

1. Introduction

In the frame of Generation IV, the French Commissariat l'Energie Atomique is developing an innovative concept of high temperature gas-cooled reactor as a promising milestone toward sustainable nuclear energy Carré et al. (2001). The use for the nuclear core of a refractory fuel with high thermal conductivity and fission product confinement capability is intended to ensure high robustness in case of accidental transients, and therefore a high level of safety and reliability. Additional advantages come from low interaction between the primary reactor coolant (pressurized helium) and the reactor physics (almost no reactivity effect, no chemical interaction). In the GFR development plan, ALLEGRO reactor is the first step toward the electricity generating prototype GFR and thus ambitions to be the first GFR ever built. Preliminary simulations performed with the CATHARE code were performed. These introductory considerations are detailed in Section 2.

For the safety analysis, a particular attention on mass and energy transfers in the core during transients is needed. As a helium compressor is used to maintain the flow in the core (the decay heat removal blower) during the depressurised transients, a special emphasis must be laid on compressor modelling, especially on off-design regimes.

In this context, a description of the turbomachinery has been developed, based on a one-dimensional approach. In the previous years we have treated the case of axial machines (Tauveron et al., 2007; Tauveron, 2010). Centrifugal machines are also of great interest and constitute a serious candidate technology for the main circulator and shutdown cooling circulator, as general and historical considerations tell us (Section 3). The objective of this paper is to provide models, which are able to describe centrifugal compressor behaviour in off-design (Section 4). An important part of the present contribution consists in validating the numerical simulations by comparison with representative experimental data. A preliminary validation process is presented in Sections 5 and 6. The model is then applied to a circulator of high temperature gas reactors (Section 7). Finally the model is used in a depressurised transient simulation of ALLEGRO concept (Section 8). Advantages

Abbreviations: CFD, computational fluid dynamics; DHR, decay heat removal; GCR, gas-cooled reactor; GFR, gas fast reactor; HTGR, high temperature gas reactor; IHX, intermediate heat exchanger; LOCA, loss of coolant accident.

* Corresponding author.
E-mail addresses: nicolas.tauveron@cea.fr (N. Tauveron), isabelle.dor@cea.fr (I. Dor).

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Nomenclature

C_p	Specific heat
DR	Diffusion ratio
M	Mach number
$\dot{m}$	Mass flow
P	Pressure
R	Radius
r	Gas constant
T	Temperature
U	Impeller velocity
V	Absolute velocity
W	Relative velocity
$\dot{W}$	Power

Greek symbols

β	Relative angle
χ	Wake/total mass fraction
ϵ	Wake/total volumic fraction
ν	Wake/jet velocity ratio
γ	Specific heat ratio
ρ	Density

Subscripts

j	Jet quantity
m	Average quantity or meridional quantity
ref	Reference quantity
u	Circonferential quantity
w	Wake quantity
T	Total quantity or tip quantity
1	Inlet quantity
2	Outlet quantity

of this model versus first preliminary simulations (where the pump module was used) are shown.

2. Reactors description and behaviour in depressurized transients

2.1. Gas fast reactors

2.1.1. Introduction

The gas-cooled fast reactor (GFR) is one of the six reactor concepts selected in the frame of the Generation IV initiative and a high priority in the French Commissariat l'Energie Atomique program on the Future Nuclear Energy Systems. On the road to a first commercial power reactor, ALLEGRO reactor ambitions to be the first GFR ever built. It is a small power experimental reactor whose objective is to demonstrate the specific GFR technologies (fuel, safety systems, etc.) and also to bring elements of demonstration for the whole gas-cooled reactors technological pathway.

The system designs are largely influenced by the (same) decay heat removal (DHR) strategy. In case of depressurised transients, DHR helium flow always relies on forced convection (the back-up pressure is assumed equal to 3 bar) whereas in case of pressurised transients, DHR helium flow relies on forced convection but in case of failure of the blower, natural convection should be efficient enough to ensure the core cooling. Therefore a specific system has been designed. It consists of three loops in extension to the vessel including a heat exchanger, located at a certain elevation in order to ensure natural convection for pressured situation, and a blower in order to start and/or maintain DHR flow especially when low pressures are reached.

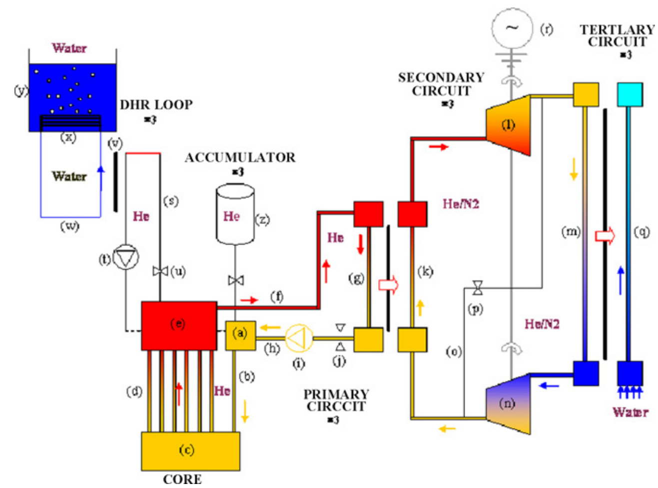

Fig. 1. Schematic drawing of the GFR. (a) Volcold, (b) downcomer, (c) lowerplenum, (d) core, (e) upperplenum, (f) hotduct, (g) IHX primary side, (h) colduct, (i) primary circulator, (j) primary isolating valve, (i) accumulators, (k) IHX secondary side, (l) turbine, (m) GV gas side, (n) compressor, (o) bypass line, (p) bypass valve, (q) GV water side, (r) generator, (s) DHR primary loop, (t) DHR circulator, (u) DHR isolating valve, (v) DHR primary heat exchanger, (w) DHR secondary loop, (x) DHR secondary heat exchanger, (y) DHR water pool.

2.1.2. GFR—indirect cycle concept

The main characteristics of this concept are a 2400-MW core based on plate type fuel elements, with an inlet temperature of 400 °C, an outlet temperature of 850 °C and a maximum fuel temperature in nominal condition of about 1200 °C. The power conversion system is based on an indirect combined cycle with helium on the primary circuit, a Brayton cycle on the secondary circuit and a steam cycle on the tertiary circuit.

A schematic drawing of the GFR is shown in Fig. 1.

The main vessel is composed as follows:

- An inlet annular volume, called volcold (a), connecting to the lowerplenum (c) via an annular pipe called downcomer (b).
- The core, represented here by six different multi-pipe nets.
- The lowerplenum (e)
- Three helium pressurised tanks (i) connected to the volcold and used for depressurised transient to maintain a medium back-up pressure of 10 bar.

The three main loops connected to the main vessel are composed as follows:

1. A primary circuit, with helium as coolant, including cross-ducts ((h) and (f)) exiting in "IHX vessel" containing a finned-plate intermediate heat exchanger (IHX) (g) and a circulator (i). An isolating valve (j) is connected to each cross-duct. This isolating valve is opened in nominal conditions and closed only for some transient cases.
2. A secondary circuit for power conversion including:

- the secondary side of the IHX (k);
- a single-shaft mounted turbomachinery ((h), (l), (r));
- a steam generator (m);
- A bypass valve (p) connected to a turbomachine bypass line (o) is used to limit turbomachine over speed or to shutdown the turbomachine. This bypass valve is closed in nominal condition and is opened only in some transient cases.

3. A tertiary steam-water circuit (q) (second part of the once-through counter-current plate-shape steam generator).