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Velocity characteristic and stability of wave solutions for a candle reactor with thermal feedback

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ABSTRACT

We study the stationary nuclear fission wave (NFW) in the CANDLE fission wave reactor analytically and numerically. The focus of this work is to elucidate in a universally applicable way the variation of wave velocity and power with respect to parameters of reactor composition and design. We also study the stability of such waves solving the time-dependent problem numerically. A one-dimensional model of an infinite cylindrical reactor with U-Pu fuel and non burnable absorber is used, including a qualitative model of thermal feedback. A new analytical approach is proposed to determine the velocity of the stationary wave. We show that there are three main mechanisms which determine the wave velocity, and thus, the power and the amplitude of the neutron flux distribution. The thermal feedback mechanism and the mechanism related to the kinetics of ^{239}Np contribute to wave velocity formation in a similar way. These mechanisms compete together with the effect of slow β-decay of ^{241}Pu. The latter dominates at lower velocities, leading to instability of the stationary wave solutions and to the existence of a minimal possible velocity of real stationary waves. Negative thermal feedback decreases wave velocity and lowers the upper margin of possible absorber densities. Under realistic conditions, both nuclear density mechanisms and thermal feedback may be important for wave velocity formation in CANDLE reactors with uranium fuel.

1. Introduction

A CANDLE reactor is a nuclear reactor in which the nuclear fission zone propagates in the nuclear medium as a solitary traveling wave (Sekimoto et al., 2001). A CANDLE reactor is also known as the traveling wave reactor (TWR) or fission wave reactor, and is based on the "breed-and-burn" concept. CANDLE could be fed by fertile raw fuel such as natural or depleted uranium, has the potential for safe and simple long-life operation, and could exhibit attractive features not yet achieved in conventional reactors (Sekimoto et al., 2001; Sekimoto, 2005; Okawa et al., 2012). Mixed uranium–thorium cores would also be possible in CANDLE. The activities of TerraPower LLC on its TWR development program (Hejzlar et al., 2013) have helped to promote the interest of the scientific community on this topic. In recent years, the number of publications and research groups investigating this topic has grown, whereas engineering challenges faced to practically implement the TWR concept have also been identified (Hejzlar et al., 2013). The concept, advantages and research history of the TWR, CANDLE and breed-and-burn reactors have been widely discussed in the open literature (Hejzlar et al., 2013; Qvist, 2013; Zheng et al., 2014; Fomin et al., 2005, 2008; Feinberg and Kunegin, 1958; Teller et al., 1996). The extensive research effort led by Prof. H. Sekimoto (Sekimoto et al., 2001; Sekimoto, 2005; Okawa et al., 2012; Sekimoto and Nakayama, 2014) has helped to develop a growing line of different CANDLE reactor designs with a variety of improved, practically attractive characteristics. These designs include: small-scale or large-scale reactors; fast spectrum sodium, lead–bismuth or Pb-208 cooled fast breeder reactors; high temperature gas-cooled reactors; reactors with uranium, thorium or combined cores.

The central element of a CANDLE reactor is the nuclear fission wave (NFW). Such a wave is self-sustained, i.e. it can exist for a long period of time without any external source, in contrast to solitary burn-up waves in accelerator driven reactors (Gaveau et al., 2005). Permanent external control of reactivity, as in conventional reactors, is also not obligatory. After the period of reactor ignition,

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CANDLE is treated in this work as a completely stand-alone dynamic system operating for an extended period of time (years) according to its inner laws under steady external conditions. Following the ignition, the profiles of power and nuclear densities, neutron flux, temperature and other fields evolve slowly towards some equilibrium state and then gradually transform into a wave of a steady shape, drifting at some velocity and reactor power which no longer change with time, as long as the approaching core end face is sufficiently far. Such a wave is referred to in this paper as "stationary wave," since all the fields do not depend on time in a reference frame moving with the same constant velocity. Theoretically, the stationary wave can be found directly, avoiding reproduction of the real dynamics of a TWR. We call this theoretical result the "stationary wave solution," to stress the difference with the result of the real evolution to the equilibrium state.

The majority of publications on TWR focus on practical TWR designs and present calculations of some parameters of a stationary wave. Nowadays there are multiple examples of such calculations done by highly precise generic multi group or Monte Carlo reactor codes (see for example Osborne and Deinert (2013), Shrestha and Rizwan-uddin (2014), Gulik et al. (2013)). Recently a reactor calculation in combination with a thermal hydraulics code (Sekimoto and Nakayama, 2014) was reported. The applied codes are based on the traditional calculation scheme for conventional reactors with the effective multiplication factor k_{eff} and fixed reactor power, average flux, or related parameters. It is important to note that the burnup calculation under the constraint of fixed power, even time-dependent, does not reproduce stand-alone dynamics of a TWR. That is why only stationary wave solutions may result from the application of such a calculation scheme.

At the same time, it is well known (a simple pendulum which has two equilibrium positions is a classical example), that equilibrium states of a dynamic system may be both stable and unstable. The same is true for nuclear fission waves. In this paper, it is first shown that stationary wave solutions may be unstable and may have no physical meaning as real waves. What concerns the already performed calculations, a special instability check is needed in every such particular case. This slow instability of NFW could hardly been foreseen within the experience of conventional reactor analysis, since it is a specific feature of TWR. Thus, having very much in common with traditional reactors, TWRs are different physically in some key aspects, and in real life their similarity may be misleading; there is a need for a special basis of qualitative understanding. Fundamental features of nuclear media determining the existence of the NFW have been outlined in classic NFW works (Feoktistov, 1989; Van Dam, 2000a). To present real stationary waves, stationary wave solutions must be stable. Their stability is considered in Section 8. Another focus of this work concerns regulation of velocity and power for a stationary NFW in the case of fine tuning of reactor parameters (Sections 5 and 6). Remarkably, a helpful direct connection exists between such velocity regulation and the possible instability of the solutions. Qualitative universally applicable conclusions are the first priority of this work, while quantitative estimates are illustrative. This work is important for TWR design. It also provides a scientifically grounded basis for the directed and efficient application of powerful reactor codes to TWR calculations, contributing in such a way to further progress in understanding practical TWR behavior.

Velocity of the stationary wave and reactor power are determined by the parameters of the reactor. These parameters include the initial material composition of the core, its radius, other parameters of the core, of the heat rejection system, as well as fixed external parameters of operation, such as the inlet velocity of the coolant flow. At fixed reactor parameters, the reactor power is completely determined by inherent self-regulation of the NFW. Fine tuning of reactor parameters leads to significant variation of the wave velocity, and the power changes in direct proportion to it practically; it is one of the key items of study in this work. This aspect seems to fall out of attention when the predominantly used calculation scheme with the effective multiplication factor k_{eff} and fixed reactor power is applied. With this scheme, the velocity corresponding to a desired and previously prescribed power is found, while k_{eff} is not exactly equal to unity as it should be. First, fine tuning of the reactor parameters leads to the variation of k_{eff} instead of the variation of the velocity, which remains almost constant due to fixed power. Second, if the reactor parameters remain fixed, real power established in the reactor naturally according to self-regulation of the wave and corresponding to $k_{eff} = 1$ exactly, differs from the previously prescribed power; it remains unknown how much the real power differs from the prescribed one. Such problems do not arise with time dependent calculations which do not involve k_{eff} and fixed power, although they are more difficult at equal accuracy. Such calculations were performed by Van Dam (2000a,b) and by the groups of Fomin et al. (2005, 2008) and Osborne and Deinert (2013).

The perturbation analytical approach to determine the velocity of the stationary wave was proposed in our previous publications (Pavlovych et al., 2008a,b,c; Khotyayintsev et al., 2010). Some of its elements corresponding to a zero order approximation are present in independent works (Gaveau et al., 2005; Chen and Maschek, 2005; Chen et al., 2005). In this paper, we include small effects of thermal feedback using a simple semi-qualitative model which may be extended in the future. In the works Feoktistov (1989), Fomin et al. (2005, 2008), Pavlovych et al. (2008a,b,c), and Khotyayintsev et al. (2010), the NFW was treated without thermal feedback. On the contrary, in the models used by Van Dam (2000a,b, 2008), only thermal feedback provides self-regulation of the NFW while the burn-out equations for nuclear densities are not included explicitly. Now the main objective is to study how thermal and concentration mechanisms work together. Analytically and numerically, we study how velocity of the stationary wave varies with variation of the absorber density and other control parameters of the reactor. We also identify mechanisms which are responsible for the velocity formation. A fast spectrum CANDLE reactor with uranium fuel is analyzed as an example, but our qualitative conclusions have a wider potential of application to a range of breed-and-burn reactors.

A numerical study specifically devoted to the stability of the NFW in a fast reactor was reported by Fomin et al. (2005, 2008). It concerns the whole period of evolution of the wave, starting from its ignition. Other simulations of the evolution of the NFW of this type are reported in the works (Van Dam, 2000a,b; Osborne and Deinert, 2013). In this work, we solve the time-dependent problem numerically, to study the stability of the corresponding stationary wave solutions. To our knowledge, such studies have not previously been reported in the open literature.

2. Basic equations and the model

The basic equations include a one-dimensional neutron diffusion equation in the one-group approximation coupled with burn-up equations. The effect of the thermal hydraulics of the reactor is taken into account implicitly, using a qualitative model of thermal feedback. The wave propagates in the axial direction in the cylindrical reactor core which is sufficiently long to be taken infinite. Within the approximation of radial buckling (Fomin et al., 2008; Chen and Maschek, 2005) the problem is reduced to an effective one-dimensional model taking into account radial leakage of neutrons. The neutron flux field $\phi(x,t)$ satisfies the following equation: