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Original Article

INNOVATIVE CONCEPT FOR AN ULTRA-SMALL NUCLEAR THERMAL ROCKET UTILIZING A NEW MODERATED REACTOR

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ABSTRACT

Although the harsh space environment imposes many severe challenges to space pioneers, space exploration is a realistic and profitable goal for long-term humanity survival. One of the viable and promising options to overcome the harsh environment of space is nuclear propulsion. Particularly, the Nuclear Thermal Rocket (NTR) is a leading candidate for near-term human missions to Mars and beyond due to its relatively high thrust and efficiency. Traditional NTR designs use typically high power reactors with fast or epithermal neutron spectrums to simplify core design and to maximize thrust. In parallel there are a series of new NTR designs with lower thrust and higher efficiency, designed to enhance mission versatility and safety through the use of redundant engines (when used in a clustered engine arrangement) for future commercialization. This paper proposes a new NTR design of the second design philosophy, Korea Advanced NUclear Thermal Engine Rocket (KANUTER), for future space applications. The KANUTER consists of an Extremely High Temperature Gas cooled Reactor (EHTGR) utilizing hydrogen propellant, a propulsion system, and an optional electricity generation system to provide propulsion as well as electricity generation. The innovatively small engine has the characteristics of high efficiency, being compact and lightweight, and bimodal capability. The notable characteristics result from the moderated EHTGR design, uniquely utilizing the integrated fuel element with an ultra heat-resistant carbide fuel, an efficient metal hydride moderator, protectively cooling channels and an individual pressure tube in an all-in-one package. The EHTGR can be bimodally operated in a propulsion mode of 100 MW_{th} and an electricity generation mode of 100 kW_{th}, equipped with a dynamic energy conversion system. To investigate the design features of the new reactor and to estimate referential engine performance, a preliminary design study in terms of neutronics and thermohydraulics was carried out. The result indicates that the innovative design has great potential for high propellant efficiency and thrust-to-weight of engine ratio, compared with the existing NTR designs. However, the build-up of fission products in fuel has a significant impact on the bimodal operation of the

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moderated reactor such as xenon-induced dead time. This issue can be overcome by building in excess reactivity and control margin for the reactor design.

1. Introduction

Space exploration and human colonization of the outer planets can be justified on the basis of it being a long-term insurance policy for ensuring the continuation of human civilization and other forms of terrestrial life. In addition, such endeavors have the potential to rapidly accelerate the advancement of science and technology, although the costs involved are likely to be high. Long-distance space missions, however, impose many challenges due to the extremely harsh space environment that necessitates life support, space radiation protection from solar flares and cosmic rays, externally independent energy sources and propellants, and numerous safety concerns. Therefore, space pioneers demand efficient and trustworthy space power and propulsion systems to reduce the mission duration, risks, and costs. At present, there are two major types of space propulsion classified according to their energy sources: chemical energy and nuclear energy. Until now, chemical rockets (CRs) have dominated most space programs based in Earth's orbit. However, manned missions to Mars and beyond, that make use of conventional CRs, will seriously suffer due to the enormous propellant requirement and correspondingly high launch costs resulting from the associated low propellant efficiency. This, in turn, could result in a longer trip time. Meanwhile, nuclear rockets have at least twice the propellant efficiency of chemical propulsion, allowing a reduction in propellant requirement and launch costs. Nuclear rocket engines can also be configured to operate bimodally, by converting the surplus nuclear energy to auxiliary electric power, required for the operation of a spacecraft. Moreover, the concept and technology of the nuclear rocket are very simple, already proven, and safe [1,2]. Considering these factors, nuclear propulsion is the most attractive option for long-distance space exploration or exploitation.

Space development is not the duty of just a few nations that are advanced in space technology. The Republic of Korea (ROK), which successfully launched the two-stage NARO rocket carrying a satellite, is also one of the volunteers in the international efforts at space exploration and the expansion of human civilization beyond the Earth. The ROK government has also recently shown extensive support for the Korean space program through its long-term space development plan, praising the success of NARO as evidence of a positive outlook. This is particularly important given that the ROK promises great potential in terms of developing space nuclear systems, as it already develops advanced nuclear technology as a major nuclear energy country, even exporting it to other countries. In fact, the ROK has already begun the research and development of space nuclear systems. The Korea advanced nuclear thermal engine rocket (KANUTER) is an innovative, ultra-small nuclear thermal rocket (NTR) engine currently being designed at Korea Advanced Institute of Science and Technology (KAIST) for future generations [3]. KANUTER has the following characteristics for meeting the leading NTR design requirements: high efficiency, compact and lightweight system, and optional bimodal capability (capable of both propulsion and electricity generation). This paper briefly introduces the general principle of nuclear thermal propulsion (NTP), and proposes the innovative concept of KANUTER by describing the system and its neutronic and thermohydraulic design features.

2. Why nuclear propulsion in space?

Nuclear-based systems can provide electricity, heat, and propulsion for space missions that are well beyond the capabilities of solar power, fuel cells, and conventional chemical systems. There are three main classifications of nuclear energy for space applications: radioisotope decay, nuclear fission, and nuclear fusion. Among these nuclear energy sources, nuclear fission energy is the most feasible option in terms of both sufficient energy density and technical maturity for high thrust propulsion missions. In particular, nuclear fission energy can power three types of space propulsion: nuclear pulse propulsion (NPP), nuclear electric propulsion (NEP), and NTP. NPP involves the detonation of small nuclear explosive devices behind a spacecraft to generate immense thrust. For shorter trips with high acceleration, an NPP system will be preferred, despite having lower propellant efficiency. This concept, however, is currently unrealizable due to the enormous radiation exposure and the Nuclear Test Ban Treaty. NEP uses a bank of electric thrusters powered by a fission reactor. Although NEP has a very high propellant efficiency, it is problematic because of its low thrust-to-weight ratio, and the low acceleration. Perhaps future missions to the outer planets (such as Jupiter and beyond) will require an NEP system. NTP directly utilizes the thermal energy of a fission reactor to heat a low molecular weight propellant producing thrust through a thermodynamic nozzle. NTP represents the most promising and near-term method for human solar system missions, because it ensures not only high thrust, but also high propellant efficiency [4–6]. This section briefly introduces the general principle, advantages and applications of the NTP system for the purpose of informing the public.

2.1. *General principle of NTR*

NTRs use nuclear fission reactors similar to those safely employed in nuclear power plants and propulsion ships. They utilize thermal energy released from the fission reactor to heat a single low molecular weight propellant, i.e., hydrogen (H_2). This is the basic difference from a CR which utilizes the