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Viewpoint article

Combustion synthesis: An effective tool for preparing inorganic materials

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ABSTRACT

Combustion synthesis is a fast and energy-efficient process to prepare inorganic materials from self-sustained combustion reactions. It is widely used for preparing ceramics, metals, and their composites. The unique condition in combustion synthesis with high temperatures and large heating rates offers good opportunities to explore new materials and novel microstructures. This paper gives a viewpoint on recent progress in combustion synthesis, from fundamentals to applications. New results on theories, processings, and materials are reviewed, and perspectives on the development of combustion synthesis are provided.

1. Introduction

Combustion is essential to the existence of human beings, and dominates power generation and transportation. Combustion is a complex phenomenon, and combustion science involves a wide spectrum of scientific disciplines, such as thermodynamics, chemical kinetics, and fluid dynamics [1–3]. Despite the long history of utilization of fire by mankind, significant advances in understanding the nature of combustion were made only from the last century. With the progress in combustion theory, a new application of combustion was developed about half a century ago [4], which is now known as combustion synthesis.

Combustion synthesis, just as the name implies, is a method to synthesize useful materials from combustion reactions, or briefly synthesis by combustion. So, what is combustion? In a textbook, combustion is defined as rapid oxidation generating heat [1]. From Wikipedia, combustion is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species [5]. According to the Encyclopaedia Britannica, combustion is a chemical reaction between substances, usually including oxygen and accompanied by the generation of heat and light in the form of flame [6]. From the definitions, combustion brings two results, viz. new substances (different from the reactants) and heat energy. In most applications of combustion, only the heat energy is wanted and the new substances are called exhausts [7]. In combustion synthesis, however, the new substances become the focus of concern. In this sense, combustion synthesis offers an alternative way to utilize combustion.

The beginning of combustion synthesis was connected with the discovery of a new combustion phenomenon of solid flame. In 1967, at the Institute of Chemical Physics, USSR Academy of Sciences, A.G. Merzhanov, I.P. Borovinskaya, and V.M. Shkiro discovered a new combustion phenomenon where all the reactants and products were solid [4,8], which was later called "solid flame". The authors realized that not only the combustion process but also the product was of interest, and consequently a novel method for preparing refractory compounds was developed and termed self-propagating high-temperature synthesis (SHS) [9]. A specific feature of SHS is to use heat released in fast combustion reactions to replace longtime heating by furnaces, which leads to a shorter processing time, lower energy cost, and larger productivity.

The studies on SHS were firstly carried out at Chernogolovka under the leadership of Merzhanov, and then spread all over the Soviet Union. In 1982, an article entitled "Self-propagating high-temperature synthesis: a Soviet method for producing ceramic materials" by J.F. Crider was published in USA [10], which initiated SHS studies there. Since 1980s, SHS research spread in the whole world with more countries involved, such as Japan, Poland, Korea, China, Italy, and Spain. With the development of SHS, the scope of SHS was extended to all processes of producing solid materials from combustion reactions, and another name of "combustion synthesis" was proposed. Now, both the terms of SHS and combustion synthesis are being used, but the latter appears to be more used and with a wider scope.

Today, the research of combustion synthesis is carried out in nearly 50 countries and every year about 300 SCI papers are published (Fig. 1). Combustion synthesis has become an interdiscipline associated with many different scientific subjects such as materials science, chemistry, and physics [11–16]. The commercialization of combustion synthesis also makes great progress. NTPF Etalon, a joint enterprise with Magnitogorsk Iron and Steel Works, was established in Soviet Union and produced nitridized ferroalloys by combustion synthesis with an

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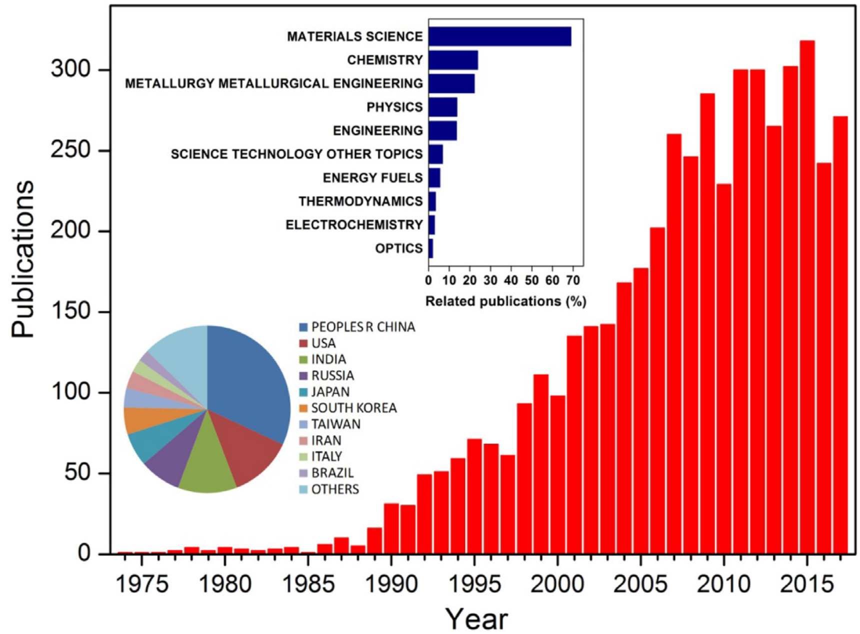

Fig. 1. A statistic of SCI publications on combustion synthesis in the period of 1974–2017. The insets show the distribution of publications by subject and country/area.

annual output of 2400 t [17]. In China, combustion synthesis is used for commercial production of ceramic-lined pipes for transferring abrasive media (10,000 t/year), TiB_2 powders (40 t/year) and evaporators (200,000 pieces per year), and ferrovanadium nitride products (10,000 t/year) [17,18].

In combustion synthesis, the reactants may be solids, liquids, or gases. Solid combustion synthesis, in which at least one reactant is solid, is most studied and will be discussed later. Liquid combustion synthesis has a good example of solution combustion synthesis, where an aqueous solution of oxides or metal salts is mixed with a fuel and heated to the ignition temperature so that combustion happens and produces ultrafine solid particles [19–21]. Gas combustion synthesis (also called flame synthesis), is a process where combustion reactions take place in gas phase, and is often used to prepare ultrafine powders [22,23]. A good example of gas combustion synthesis is the production of carbon black, which has a long history and dates from the ancient times.

This paper gives a viewpoint on recent progress in combustion synthesis, from fundamentals to applications. New results on theories, processings, and materials are reviewed, and perspectives on the development of combustion synthesis are provided. Due to the page limit, the following discussion is focused on solid combustion synthesis.

2. Fundamentals of combustion synthesis: theories

Combustion synthesis can be operated in two modes, viz. propagation and volume reaction (also called thermal explosion). In the propagation mode, the reaction is initiated by ignition at one point and then spreads over the sample by the propagation of reaction front (Fig. 2(a)). In the volume reaction mode, the whole sample is heated to the ignition temperature so that combustion reaction occurs simultaneously everywhere in the sample. In practice, it is difficult to ensure that the temperature is strictly uniform and the reaction happens exactly at

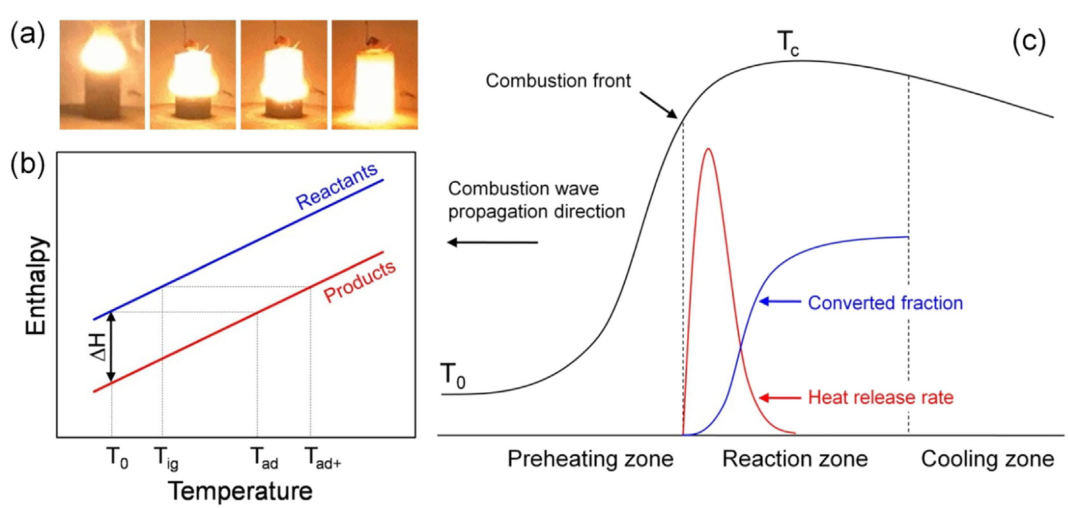

Fig. 2. (a) Photographs showing the propagation of reaction front in combustion synthesis; (b) a schematic illustration of enthalpy-temperature correlation in combustion reactions; (c) a typical structure in the region neighboring the reaction front.

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