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Experimental studies on shock wave and particle dynamics in a needle-free drug delivery device

Guang Zhang [a], Ik In Lee [a], Tokitada Hashimoto [b], Toshiaki Setoguchi [c], Heuy Dong Kim [a,*]

[a] *Department of Mechanical Engineering, Andong National University, Andong, Republic of Korea*
[b] *Advanced Technology Fusion, Graduate School of Science and Engineering, Saga University, Saga, Japan*
[c] *Institute of Ocean Energy, Saga University, Saga, Japan*

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A B S T R A C T

Recently a needle-free drug delivery device as an innovative injection device has been widely used in medical fields. Drug powders induced with the high momentum by a moving shock wave can be directly delivered into skin layers. The main component of this device is a contoured shock tube, which consists of a micro shock tube and an expanded nozzle. Drug powders and gas flows are induced by a moving shock wave generated in the micro shock tube and accelerated in the expanded nozzle. The most difficult operation is that the momentum of drug powders should be strictly controlled. In present experimental studies, a micro shock tube was designed to investigate the shock wave propagation. A sonic or a supersonic nozzle installed at the exit of the micro shock tube was studied to observe the particle acceleration. Different diaphragms for initializing incident shock waves were investigated as well. Particle tracking velocimetry (PTV) measurement was carried out to investigate the motion of solid particles. In order to visualize the shock wave propagation, Schlieren visualization method was also carried out. The primary incident shock wave and the reflected shock wave induced by the closed end of the driven section were clearly observed.

1. Introduction

A needle-free drug delivery device, which mainly consists of a micro shock tube and an expanded nozzle, has been widely used for injecting drug powders or liquid drops in medical engineering. Particle-gas flows are initialized in the high speed by a moving shock wave generated in the micro shock tube and accelerated again in the expanded nozzle. By this way, drug powders can acquire high momentum to be delivered into expected skin layers. This device can accelerate drug powders with 2 μm–50 μm in the diameter to 200 m/s to 1000 m/s. Drug powders have enough momentum to penetrate human skin and be delivered into epidermal layers at those speeds. Compared to traditional syringe delivery devices, a needle-free drug delivery device is more convenient and easier to be operated. Patients experience less pain and skin injury without sharp needles and the risk of the cross-contamination is also reduced without the repeated use of needles. A needle free drug delivery device has no disposal issues and solid drug powders can be directly injected. In addition, patients can finish the injection by themselves instead of nurses [1–4].

A micro shock tube is mainly used for generating the incident shock wave and inducing drug powders with high momentum in a needle-free drug delivery device. A micro shock tube consists of a driver section and a driven section which are separated by a diaphragm. The driver section is always initialized in the high pressure and the driven section keeps in the low pressure. Due to the pressure difference between two sections, as the diaphragm is ruptured, an incident shock wave is developed and particle-gas flows are induced by the incident shock wave. The shock wave carries high energy which can lead to damage to the human body. Therefore, the strength and propagation of the incident shock wave should be carefully handled when a needle-free drug delivery device is used for the injection.

Particle-gas two-phase flows show greatly different behaviors from the single gas flow, especially in the supersonic regime. Flows with solid particles need more momentum to be accelerated, which means that the presence of particles attenuates multiphase flows compared to the single gas flow. High temperature region takes place behind the incident shock wave, so heat transfer occurring

* Corresponding author.
E-mail address: kimhd@anu.ac.kr (H.D. Kim).

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between particles and the gas phase also makes the decay of the flow motion. Due to the inertia and resistance, particles always follow shock waves improperly, which make it difficult to study the particle motion in supersonic flows, especially for experimental studies.

Brouillette [5] investigated effects of the scale on the shock wave propagation experimentally and theoretically in a micro shock tube. Pressure measurements were performed to calculate shock wave Mach number. Shock wave Mach number was lower in the experimental studies compared to that in the theoretical analysis. In addition, The incident shock wave gradually attenuated as it moved in a micro shock tube. Arun et al. [6] carried out a computational study on the diaphragm rupture process at high and low diaphragm pressure ratios respectively. At a high pressure ratio, the diaphragm rupture was regarded to be instantaneous and complete, while the diaphragm was partially ruptured at a low operating pressure ratio or a thick diaphragm used. The partial rupture was observed to initialize the flow and the incident shock wave complexly.

Mcbride [7] and Raghunath [8] used Pitot tubes to investigate flows in supersonic nozzles. Pitot tubes with different diameters were performed to study their effects on pressure measurements. The pressure from Pitot tubes with larger diameters was closer to the real pressure of the flow and the limit of Pitot tubes with a larger diameter was shown to be rather smaller. Schlieren visualization method was used to visualize shock waves generated in a wind tunnel by Xie et al. [9]. Shock waves induced by supersonic flows through wedge-shaped models were clearly observed.

Tungsten particles with the diameter of 1 μm–5 μm were accelerated to be around 300 m/s by using compressed nitrogen in a shock-driven device [10]. This speed induced by a shock wave was tested to be enough to allow particles to reach the specified epidermal layers. Kendall et al. [11–13] carried out pressure measurements, Schlieren visualization method and particle image velocimetry (PIV) to investigate gas-particle flows in a contoured shock tube (CST). The velocity and propagation of incident shock waves were obtained. In addition, the velocity of particles was measured as well. Rasel et al. [14] carried out numerical studies on optimizing the design of the contoured shock tube for a needle-free drug delivery device. Different shock tube length and diaphragm pressure ratios were investigated. The particle velocity and motion were observed and compared at different operating conditions.

Particle motion in supersonic flows was investigated by laser Doppler velocimetry by Tedeschi et al. [15]. Different drag coefficients were discussed and a new expression of the sphere drag coefficient has been proposed. The particle velocity was obtained to calculate drag coefficients and compared to theoretical results. The experimental approach used for evaluating the response time of particles across a stationary shock wave was assessed by the way of PIV measurement by Ragni et al. [16]. The response time of different particles across an oblique shock wave of Mach 2.0 was also investigated. Fincher [17] provided the details on the diameter of drug powders used for being injected into the human body in medical fields. The diameter of particles used for present experimental studies was referred to the average diameter of drug powders given in the reference.

In this paper, a micro shock tube and different nozzles which were assembled into different contoured shock tubes (CST) were designed and experimentally investigated. In order to investigate effects of different diaphragms on the generation and propagation of incident shock waves, pressure measurements and Schlieren visualization method were carried out. Particle-gas two-phase flows induced by sonic and supersonic nozzles respectively were also studied by using Pitot tube measurements and particle tracking velocimetry (PTV). The particle velocity showing flow characteristics was obtained at the nozzle exit by installing sonic or supersonic nozzles at the exit of the micro shock tube. In addition, particle number distributions were also obtained.

2. Experimental methods

2.1. Experimental facility

The main components of the experimental micro shock tube are schematically shown in Fig. 1. The length and the diameter of the driver section are respectively 41 mm and ϕ20 mm. The driven section has the length of 66 mm and the diameter of ϕ7.5 mm. A larger driver section was selected as the results of that it is easier to make the connection between the driver section and the high pressure tank. In order to ensure that the diaphragm was ruptured instantaneously, the movable needle was installed in the vertical direction and adjacent to the diaphragm in the driver section. Particles were seeded at the inlet of the driven section before the diaphragm was set and tensed as shown in Fig. 1. After the diaphragm was ruptured, particles were initialized in high momentum and moved by following the incident shock wave.

2.2. Pressure measurement

There are two pressure transducers installed for recording the static pressure changes in the driven section. Pressure transducers were chosen from Kulite XTL-190 (M) series. The installation of pressure transducers is quite easy and they have the high natural frequency as well as the high sensitivity. Based on the distance between two pressure transducers and the time difference of the incident shock wave moving through two pressure transducers, the velocity of the incident shock wave can be calculated. In the present experimental studies, particle-gas flows induced by sonic and supersonic nozzles were also investigated. Different flow characteristics were shown in sonic and supersonic nozzles even though the same pressure conditions were initialized. Sonic and supersonic nozzles were installed at the exit of the micro shock tube and the detailed size is shown in Fig. 2. The long tube of the sonic nozzle was designed because of the convenient installation of the pressure transducer. Due to the small diameter of the nozzle inlet, the closed end was regarded in the driven section. As the incident shock wave was reflected, the high pressure was induced behind the reflected shock wave in the driven section. This high pressure was

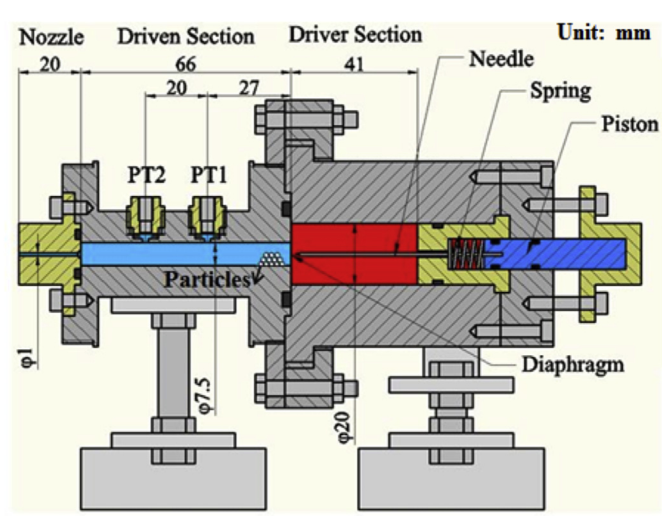

Fig. 1. Schematic of the micro shock tube model.