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ANT-MAN AND THE WASP: MICROSCALE RESPIRATION AND MICROFLUIDIC TECHNOLOGY

ANNE STAPLES,* AND MAXWELL MIKEL-STITES

Engineering Science and Mechanics Program, Department of Biomedical Engineering and Mechanics, Virginia Tech, Blacksburg, Virginia, USA 24060

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*** Corresponding author: aestaples@vt.edu**

ABSTRACT

Insects and other terrestrial arthropods, benefitting from millions of years of evolutionary refinement, manipulate fluids efficiently, including their bodily fluids, air, nectar, and water, at the microscale in their daily lives. Microfluidic technology, though far behind insect fluid handling in terms of performance, is a rapidly developing field, which allows traditional laboratory testing spaces, occupying hundreds of square meters, to be shrunk down to chips occupying less than a square centimetre. These lab-on-a-chip microfluidic devices are positioned to revolutionize fields like exoplanetary composition testing and single cell biology studies, and can provide inexpensive, ubiquitous environmental monitoring and global health testing. Microfluidic technology, in addition, has the potential to bridge the gap between Ant-Man and the Wasp's human respiratory apparatuses, and the more optimal ones that insects use to breath at the microscale, to help them overcome issues when they shrink in their suits like the "death zone dilemma" and a relative air density similar to that near the peak of Mt. Everest.

PROLOGUE

Scott sprints across the concrete of the parking garage, surrounded by a swarm of fire ants his size, while Hope flies past above. Approaching a crack in the wall, Scott's breath echoes in his helmet and the abdomens of his hexapedal allies pulse rhythmically as they run alongside him. Finally, having reached the crack, they all have a chance to pause and catch their breath, while Hope hovers impatiently above their heads.

JULY 2018
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INTRODUCTION

Scott Lang, also known as Ant-Man, and Hope Van Dyne, also known as the Wasp (See Figure 1), are two of the most recent additions to the Marvel Cinematic Universe (MCU), though they first appeared in comic books by Marvel Comics in 1962 (Ant-Man) and 1963 (the Wasp). Like Tony Stark, also known as Iron Man, another character from the MCU [1, 2], their powers are drawn from suits with sophisticated technologies that they put on to assume their superhero forms. While in their suits, Ant-Man and the Wasp may shrink to the size of insects and retain their full-size strength [3], but are able to manipulate their mass, when necessary, as shown in the recently released 2018 film, *Ant-Man and the Wasp [4]*.

The core technology behind Ant-Man and the Wasp's suits are Pym particles. The particles were discovered by Hank Pym, a former scientist with S.H.I.E.LD., the espionage and counter-terrorism agency that appears in American comic books published by Marvel Comics, various television series, and films in the MCU. According to the films [4, 5], Pym particles allow for a reduction or expansion in the distance between atoms in matter [3]. The particles can also apparently manipulate mass; a micro-sized Ant-Man cracks the tile on the bathroom floor when he falls out of a tub the first time he puts the suit on, and can pack a full-sized punch, implying a high mass. However, Ant-Man can also ride on the back of an ant and run up the barrel of a gun without causing the assailant to drop it, implying a low mass (Figure 2). It has been suggested that this may be accomplished by the moving of mass into other unseen spatial dimensions [6].

Similar to other members of the Avengers such as Hawkeye [1, 7, 8], the Winter Soldier [9], and Iron Man [1, 2], the science behind Ant-Man's abilities has been the subject of scientific investigation. There has been much informal discussion on sites like Quora, Reddit, and Stack Exchange about the fundamental physics of Ant-Man (see Refs [10-12]), as well as popular writing by scientists, including the excellent series of Ant-Man physics articles on Wired.com by Rhett Allain [6, 13-15], a physics professor at Southeastern Louisiana University. Additionally, James Kakalios, a distinguished professor of physics at the University of Minnesota and the scientific consultant for the Ant-Man movies and other films like *Watchmen* and *The Amazing Spider-Man*, has spoken to science reporters about the physics of Ant-Man and the Wasp [16-18]. Kakalios also wrote a book called *The Physics of Superheroes* that discusses the physics of Ant-Man [19]. These discussions have mostly centred on the physics of shrinking and its implications for mass, force, and rotation rates at the microscale; discussions of how the suit works; discussions on the implications of Ant-Man shrinking down into the sub-atomic quantum realm; and discussion on some fundamental metabolic difficulties Ant-Man and the Wasp would face if they retained their mass but were micro-sized, e.g., insufficient body surface area to dissipate heat.

Here, we explore the problems associated with a human breathing at the scale of an ant. How are the respiratory strategies used by ants and other insects different from those of mammals like humans and other large organisms, and why? And how might Dr. Pym's suit compensate for the difference so that Ant-Man and the Wasp can maintain an adequate oxygen supply in their suits? We suggest that Dr. Pym may have made use of microfluidic technologies to handle air at the microscale

JULY 2018
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efficiently, and use the example of Ant-Man and the Wasp's possible breathing mechanisms to discuss microfluidic lab-on-a-chip technology. Such devices are at the forefront of important efforts to design miniaturized and inexpensive medical testing [20] and disease monitoring devices for global health applications [21], air and water quality monitoring devices [22], and testing machinery in many other fields [23]. Nanofluidics will also play a role for Ant-Man and the Wasp. Notably, the smallest blood vessels in their cardiovascular systems will approach nanoscale diameters when they shrink to insect size. The fundamental physics considerations for blood flow through nanoscale vessels, however, are significantly different from those for airflow through respiratory systems, which have shrunken to the microscale. Here we will only discuss the latter case.

OXYGEN DELIVERY PARADIGMS IN HUMANS AND INSECTS

Almost all living animals need to deliver oxygen to their cells. The notable exceptions are the anaerobes, of which there are only a few hundred species including bacteria, protists and some deep-sea worms. The cells of all other animals contain mitochondria, the organelles that use oxygen to power the cell. In the cells, oxygen is used in metabolic processes. One example of a cellular metabolic process is the Krebs cycle, a series of chemical reactions used by all aerobic organisms to release stored energy. In the Krebs cycle, cells release stored energy by combining oxygen with molecules made from carbohydrates, fats, and proteins. These molecules are converted into carbon dioxide and chemical energy in the form of adenosine triphosphate (ATP), the so-called "molecular unit of currency" of intracellular energy transfer, which is found in all forms of life [24].

In single-celled organisms, such as bacteria, some algae, and protozoa, oxygen can be delivered by simple diffusion across the cell membrane, with oxygen atoms moving through the organism from regions of high concentration to low, at a rate proportional to the difference in concentrations. However, the relatively slow diffusion rate of oxygen compared to carbon dioxide limits the size of these organisms. For complex multicellular organisms, sophisticated delivery systems akin to highway networks have evolved by necessity, since the membrane of every cell is no longer in direct contact with air. In humans, for example, the mean distance between adjacent capillaries, the smallest blood vessels in the body, is about 25 microns in myocardial (heart) tissue, 40 microns in the brain's cortical tissue, and 80 microns in skeletal muscle tissue [25]. Amazingly, in the average-sized human, there are so many blood vessels that, put end-to-end, they reach a length of about 100,000 km, which is enough to encircle the Earth two-and-a-half times [26]! As we will see in more detail, higher organisms (defined here as complex multicellular life) can be separated into two groups based on their respiratory strategies. Insects and some similarly sized terrestrial arthropods, which do not use blood as an intermediate oxygen carrier are in one group and all other higher organisms, including humans and other mammals, birds, reptiles, amphibians, and fish, which do use blood, in the other [27]. In this paper, we call mammals and other higher organisms, Group A, and insects and other small terrestrial arthropods Group B.

JULY 2018
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Figure 1: Hope Van Dyne, the Wasp (left) and Scott Lang, Ant-Man (right). The designs of their suits include the insect faces their characters are based on [28].

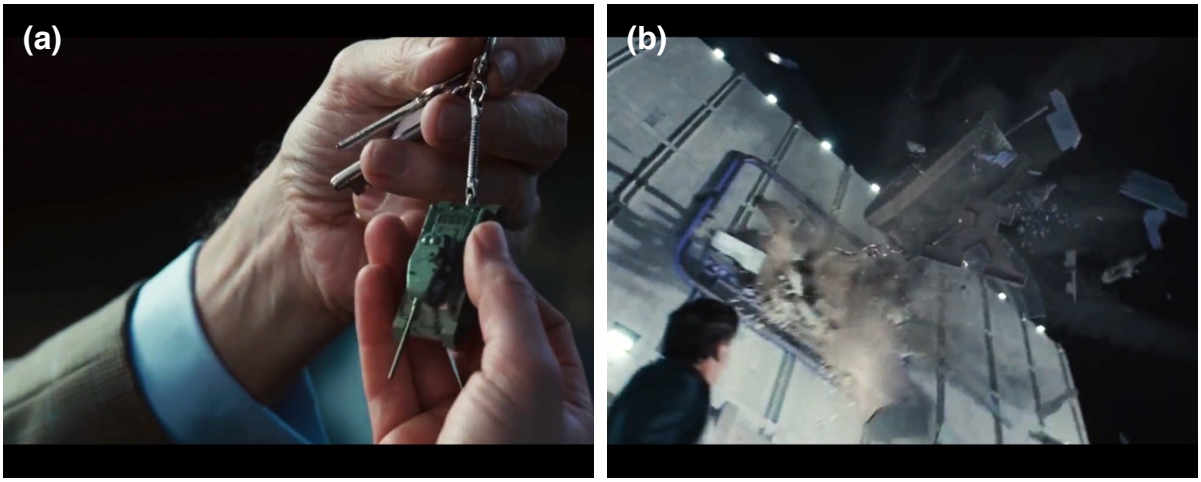

Figure 2: (a) Dr. Hank Pym carries a T34 military tank shrunk down so that it fits on a keychain. The mass of the tank is clearly not conserved after its interaction with Pym particles. (b) The same tank re-expanded to its original size. The now enlarged keychain is visible making contact with the wall [5].

Humans like Scott Lang and Hope Van Dyne, and other members of Group A, use coupled respiratory and circulatory systems, connected in series, to deliver oxygen to cells. The cells can only survive within a small radius of an oxygen-delivering capillary. The entrance to the respiratory system is through the nose and mouth, which guide air into the trachea, the largest structure in the respiratory system, which is about 1.5 - 2.0 cm in diameter [29]. The trachea branches into the main left and right bronchi, and the respiratory tract then goes through approximately twenty more branchings (see Figure 3(a)) until the terminal

JULY 2018
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alveolar sacs are reached. Here, gas exchange occurs across the alveolar tissue into and from a fine mesh of capillaries, which cover about 70% of the alveolus' area. Typical human lungs contain about 700 million alveoli, resulting in about 70 m^2 of respiratory exchange surface area [30]. In mammals, the alveolar size scales proportionally to body size (see Fig. 4 of Ref. [31]). The capillaries collecting oxygen at the alveolar surface reunite and pool their freshly oxygenated blood together into the left atrium of the heart via the pulmonary veins. The heart then pumps the freshly oxygenated blood throughout the body via the arterial system, which branches into capillaries that are on average 80 microns apart in skeletal tissue, to all approximately 10^{13} cells. Fibroblasts (connective tissue cells that are about 10 to 15 microns in diameter) are at most about four cell widths away from an oxygen source [32].

In comparison, insects and other members of Group B transport air that contains oxygen directly to the cells in their respiratory systems, without using a circulatory system. The air is transported via a complex network of thousands of respiratory tubes called tracheae that branch and decrease in diameter until they reach the cells (see Figure 3(b)). Insects usually have 6 to 11 pairs of air intake locations, called spiracles, located laterally around the abdomen and thorax, generally with one pair per body segment. The diameter of the tracheal tubes at the spiracles can be as large as several millimetres, though this depends on the species. At the cells, however, the tracheal tubes terminate in tracheoles that are about 1 micron or less in diameter. Similar to human capillaries, the spatial distribution of tracheoles – the ultimate oxygen delivery channels to the cells, varies with tissue type, but does not scale significantly with the organism's mass. In insect flight muscles, for example, where metabolic demand is highest, nearly every mitochondrion within a cell is in contact with a tracheole [33].

Hence, the main differences in gross respiratory structure and organization between Groups A and B are the use of a circulatory system in Group A, and not in Group B, and the localized intake of oxygen in Group A, and distributed oxygen intake in Group B. The reasons for these differences are that smaller organisms can breathe more easily by diffusion than larger organisms due to the relatively smaller distances oxygen and carbon dioxide must travel, and that the apparent air density is lower for micro-sized organisms than for macro-sized ones. For example, when the Wasp is human sized approximately *N* air molecules span her height from head to toe. But when she is insect sized, about a factor of 140 times shorter, only about *N*/140 air molecules span her height, leading to a lower apparent air density. Both these conditions suggest a respiratory strategy with multiple air intakes so that the appropriate amount of oxygen molecules is distributed to the cells. Insects are, in fact, limited in size because of the distance that oxygen can diffuse into the tracheal system while providing the necessary density of oxygen molecules [34]. On a final related note, Kleiber's law, a fundamental observation in biology whose physical reasoning is poorly understood, states that an animals' metabolic rate (*R*) scales with their total mass (*M*) to the power of ¾ [35]

$$R \propto M^{3/4}. \qquad (1)$$

Thus, a large human with a mass of about 10^8 times more than a small worker ant will consume only about 10^6 times more energy in the same time span.

JULY 2018
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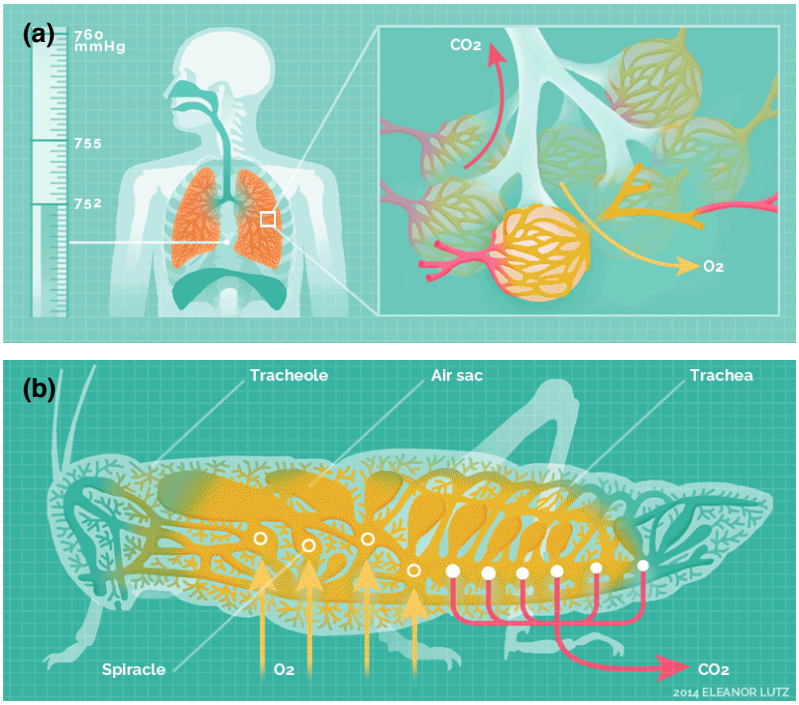

Figure 3: (a) The human breathing paradigm. Air is brought into the lungs via a single opening and oxygen is circulated to the body's cells via the cardiovascular system. Gas exchange happens in the lungs across the alveolar surface. (Insert shows the gas exchange surface.) (b) The insect-breathing paradigm. Air is brought into the body through several openings called spiracles and brought directly to the cells via a network of respiratory tubes called tracheae. Gas exchange happens directly at the cells across the surfaces of the terminal tracheal tubes. Images modified from Ref. [36]. Both human and insect respiratory air pressures are generally in the range of tens to hundreds of millimetres of mercury.

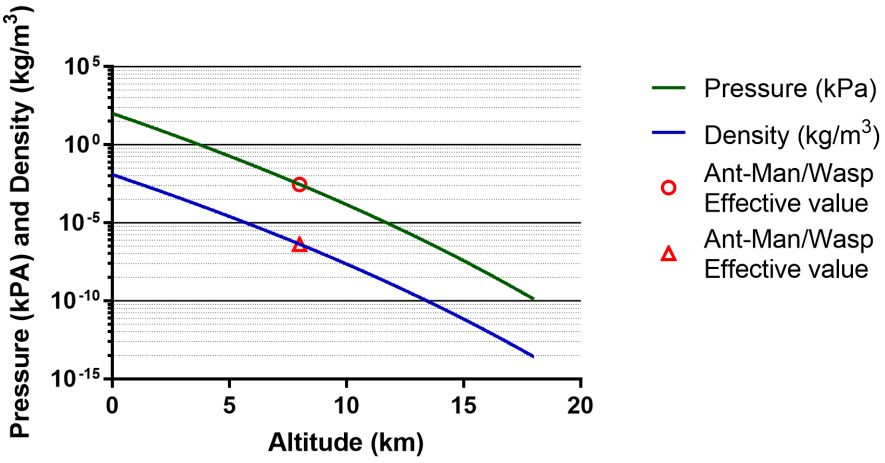

Figure 4: Semi-log plot of the Earth's atmospheric density and pressure as a function of altitude. The effective values that Ant-Man and the Wasp experience when they shrink to the microscale are indicated with the red triangle (pressure) and red circle (density). See the Appendix for the MATLAB code that performs these calculations.

JULY 2018
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RESPIRATORY CHALLENGE FOR MICROSCALE HUMANS

As we have seen, the respiratory strategies that have evolved for microscale organisms are significantly different than for macroscale organisms. Microscale organisms breathe primarily by diffusion and have a higher metabolic rate per unit mass than macroscale organisms. This means that when Ant-Man and the Wasp shrink to about 1/140 their original size (Scott Lang's height is given as 1.8 meters [6], and a typical ant has a length of 0.0127 meters), there are two immediate respiratory problems. First, a huge challenge is that the effective atmospheric density experienced by Lang and Van Dyne when they shrink is as if they were on a mountain the height of Mt. Everest, approximately 8 km – at the beginning of the so called "death zone" above which mountain climbers cannot adapt to the reduced oxygen levels naturally. This is because the molecules that make up the air surrounding them appear farther apart when they are 1/140th of their original size (see Figure 4 and the Appendix). Second, Kleiber's law (equation 1) implies that either a) Lang and Van Dyne's metabolic demands will be massively higher than for a 'normal' microscale organism, assuming their mass is conserved, as their metabolic needs will still be those of a full-sized human, or b) Lang and Van Dyne's metabolic demands will be greatly reduced, and brought in line with other microscale organisms if their masses scale down to typical insect masses, as is implied in scenes of Ant-Man riding his friend Ant-thony, a carpenter ant [37], and in other scenes in the films (see Figure 2).

In the following analysis we will assume that we are dealing with case b) and Lang and Van Dyne's masses and metabolic needs are reduced to the insect-scale when they shrink. In this case, assuming the same 10^8 mass difference ratio between macroscale and microscale as before and using the macroscale mass of 86 kg for Scott Lang given in Ref. [6], his microscale mass is 0.86 mg. At full size with a mass of 86 kg, Scott Lang's basal metabolic rate per unit mass should be approximately 22 kcal/kg·day, according to data published by the United Nations' Food and Agriculture Organization [38]. At the microscale, however, according to Kleiber's law (Equation 1), Scott Lang's specific basal metabolic rate (his basal metabolic rate per unit mass) will be 2,200 kcal/kg·day, a factor of 100 higher than an equivalently sized organism. Meeting this increased demand will require an equivalent hundredfold increase in his relative rate of oxygen consumption. Humans, however, have a limited metabolic range; metabolic expenditures of 10 times the basal metabolic rate (which is less than what would be required in this case) are considered extreme [39]. For example, competitive swimmers may (during training) possess a basal metabolic rate a factor of approximately three to six higher than the average human, based on caloric intake. Assuming Hope Van Dyne has a mass of 60 kg at the macroscale, the Wasp has a mass of about 0.60 mg and will face the same issues breathing at the microscale as Ant-Man. There seems to be no way to avoid the need for both a microscale compressor to deal with the "altitude problem" and a filter that will create elevated oxygen levels in the air taken into the suit in order to meet the greatly increased (proportional to their size) metabolic demand. Additionally, the O_2 molecules contained in the compressed air must be shrunk down proportionally so that they can still diffuse through the alveolar walls and capillary walls. So, the technology required for Ant-Man and

JULY 2018
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the Wasp to be able to breathe in their suits is a combination of an air pump, a compressor, and a molecular filter including Pym particle technology. While comic books depictions of Ant-Man and the Wasp have included pictures with open-masked suits, the MCU suits include enclosed helmets that could contain the necessary respiratory assistance equipment. Key to functionality of this respiratory system for the Ant-Man and Wasp suits may be advanced microfluidic technologies.

MEMS, NEMS, AND LAB-ON-A-CHIP MICROFLUIDIC TECHNOLOGIES

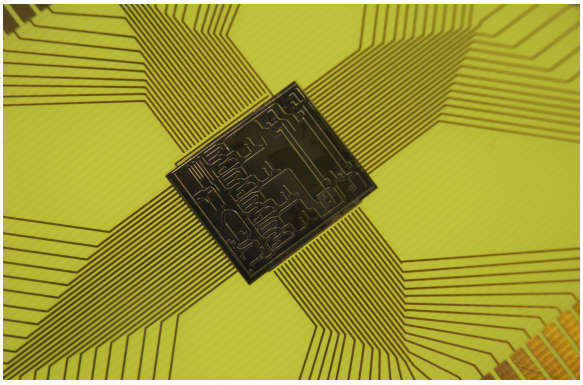

Figure 5: A lab-on-a-chip microfluidic device for genome analysis with tens of microfluidic channels. Reproduced from Ref. [40].

Microelectromechanical systems (MEMS, often called “micro systems technology,” or “MST” in Europe), nanoelectromechanical systems (NEMS), and lab-on-a-chip devices (sometimes called “micro total analysis systems,” or ”μTAS” in the chemical analysis context) are related and sometimes overlapping technologies. In each type of technology, mechanical, and often chemical and electrical components are integrated into a single device or integrated circuit, often called a “chip” that is just a few square millimetres or centimetres in size [41-44]. MEMS components can be applied as far as the microscale range (10^{-6} meters), NEMS components reach the nanoscale range (10^{-9} meters) and lab-on-a-chip devices often handle extremely small volumes of fluids, down to picolitres (10^{-12} litres) or less. Integrated circuits - first manufactured in 1958 at Texas Instruments by Jack Kilby, who won the Nobel Prize in Physics for them in 2000 - could be considered the first MEMS devices [45]. While MEMS and NEMS devices can serve a variety of purposes or functions, including giving your smartphone some fantastic capabilities [46], lab-on-a-chip devices (Figure 5) seek to scale down whole laboratory processes onto a chip for the purposes of automation and high-throughput analysis and testing [47]. Biological and medical applications like molecular diagnostics, stem cell engineering, genomics, proteomics, point-of-care medical diagnostics, and single-cell analysis drive many recent innovations in lab-on-a-chip technology [48-52].

There are unique physics challenges when handling fluids at the microscale. Forces proportional to surface area, such as the surface tension forces that occur at liquid-gas interfaces, pressure forces, and viscous forces become much more prominent at the microscale in comparison to the macroscale. This explains why there are insect water striders, but no elephant water striders. At the macroscale, forces proportional to volume, like gravity, electromagnetic forces, and forces due to accelerations other than gravity, tend to dominate [53]. These differences between forces at the micro- and macroscale emerge because as an object shrinks, its surface area decreases more slowly than its volume. For example, a cube of side length L has a surface area of $6L^2$ and a volume of L^3, leading to a surface area-to-volume (SAV) ratio of $6/L$. As the length of the cube, L, is reduced, the SAV

JULY 2018
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ratio increases. This trend is true, in general, for all shapes, including the rectangular channels commonly found in lab-on-a-chip and other microfluidic devices fabricated using standard soft lithography techniques [54]. Practically, this means that fluid mechanics at the macroscale is often inertia-dominated in response to various accelerations, which results in phenomena like turbulence, lift, and drag. However, at the microscale, fluid mechanics is often dominated by the viscous or dissipative forces that occur when the fluid is in contact with the channel and container walls. This further implies that the strategies that are efficient for handling fluids at the microscale, including those for pumping, compressing, and molecular sorting, differ significantly from those that are efficient at the macroscale.

One approach to building more efficient microfluidic devices is to take a lesson from nature. Insects, spiders, and other bugs actively handle fluids at the microscale. The honeybee, for example, manipulates air, water, nectar, honey and its own body fluids, all at the microscale. These fluids span the range of gases, (fluids which are easily compressed; e.g., air), Newtonian liquids (incompressible fluids which deform at a rate that is linearly proportional to the applied force; e.g., water), and non-Newtonian liquids (incompressible fluids which deform at a rate that is not linearly proportion to the applied force; e.g., honey). We can infer phenomenal performance parameters, too, since insect metabolic ranges—which are directly proportional to oxygen consumption—are unparalleled in the animal kingdom [55]. The same honeybee that handles air, water, and honey so efficiently can change its metabolic rate by a factor of 100 almost instantaneously. For example, when a honeybee takes off in flight from rest, its metabolic rate immediately changes. Figure 6 shows an example of a recent insect-inspired microfluidic device in which the flow in a channel is produced by collapsing the channel ceiling in a way that mimics caterpillar locomotion. In spite of this wealth of "naïve expertise" in handling fluids at the microscale, the fundamental mechanics of how insects handle fluids is just beginning to be explored [56-61].

COULD MICROFLUIDIC TECHNOLOGIES REALLY HELP ANT-MAN AND THE WASP

As we determined earlier, for Ant-Man and the Wasp to be able to breathe at the microscale and successfully avoid hypoxia, a number of connected mechanical components need to be built into their (sealed) suits. These components and function are presented in Table 1. These mechanical components would only operate at the microscale when Ant-Man and the Wasp are at the microscale. Therefore, current microfluidic technologies may be able to solve the respiratory challenges that Ant-Man and the Wasp face in their suits at the microscale. These microfluidic technologies would be inefficient at the macroscale, and could be simply deactivated when the suit is once again at the human-scale. By constructing the devices far larger than normal, when Ant-Man and the Wasp shrink to insect size these microfluidic technologies will be microsize, and operating in the regime in which they are most efficient. Relevant existing technologies for the suit are also provided in Table 1. While there are a number of microscale compressors available to address the issue of compressing air at the scale [62], for brevity, we do not discuss those technologies here.

JULY 2018
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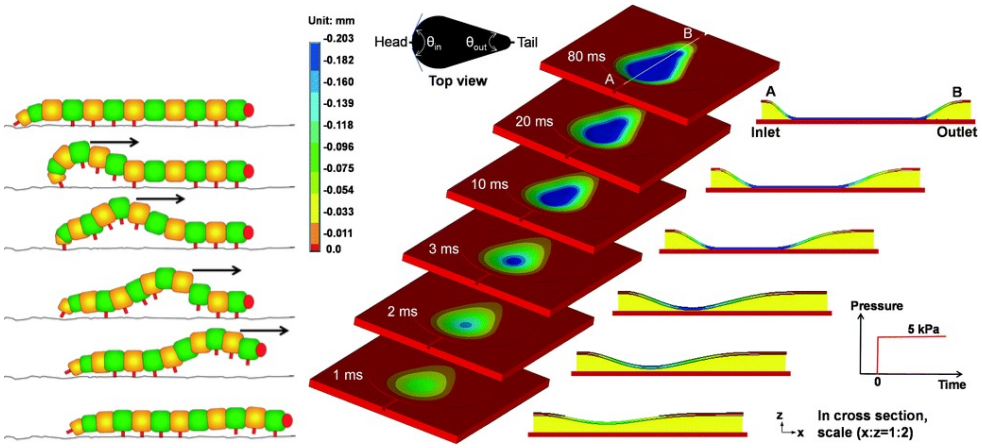

Figure 6: A caterpillar-inspired microfluidic device. In the device, flow is produced by a collapsible membrane whose shape is tuned so that the collapse mimics caterpillar locomotion. Adapted from Ref. [63] with permission of the Royal Society of Chemistry.

Table 1: Principle components, function and existing technologies that can be used to duplicate the components for the breathing system of the Ant-Man or Wasp suits. Unfortunately, the Pym particle, or an equivalent particle, has not yet been fabricated or created, which means that the shrinkage of oxygen molecules for the suit is currently impossible to achieve.

Component	Function	Existing Technologies
Pump	Draw air into the suit	Knudsen pump [64]
Compressor	Compress air to effective zero-altitude density and pressure relative to reduced size	Microscale compressors [62]
Molecular filter	Increase oxygen content of the air by filtering out other components to meet enhanced metabolic demands per unit mass due to Kleiber's law.	H-filter [65]
Pym particles	Shrink oxygen molecules to correct size for diffusion through reduced-size alveolar tissue pores and capillary pores	Awaiting fabrication/discovery

JULY 2018
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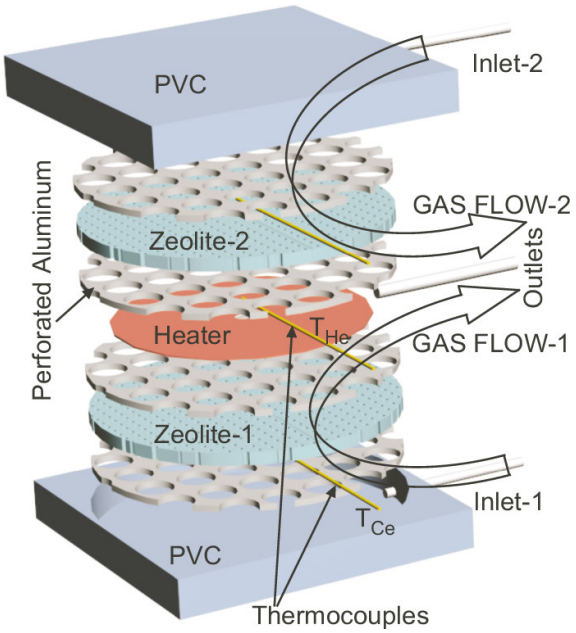

Figure 7: Close-up view of a clinoptilolite-based gas pump depicts how gas flows through the nanoporous mineral from the cold to hot areas via thermal transpiration. The two clinoptilolite disks (labelled Zeolite-1 and Zeolite-2) are 2.3 mm thick and 48 mm in diameter. Reproduced with permission from [64].

For the pump in the Ant-Man and the Wasp suits, several types of microscale pumps exist with large variations in size, range of pumping rates, pumping pressures, operational voltages, power consumption, and process compatibility with other parts of the system. Yun and Yoon [66] classify microscale pumps into two categories: indirectly-driven micro-pumps and directly-driven micro-pumps, based on whether the fluid molecules are directly acted upon or not. The commonly used peristaltic and syringe micro-pumps, for example, are given as examples of indirectly-driven micro-pumps. On the other hand, electro-osmotic and magnetohydrodynamic micro-pumps are given as examples of directly-driven micro-pumps. Further examples of micro-pumps are provided by Yun and Yoon and the references contained within [66]. For portable systems, like the Ant-Man and the Wasp suits, low power consumption and operational voltages are major considerations in selecting a pump. One attractive option could be a Knudsen micro-pump [67], because it has no moving parts and operates in response to thermal gradients alone. These thermal gradients should exist across the Ant-Man and the Wasp suits because the specific rates of their metabolic processes, which produce heat, will be proportionally increased by a factor of 100 due to their decreased relative size. They will almost certainly need cooling systems in their suits to dissipate this extra heat. Some of this waste heat could be used to drive their respiratory machinery. In one realization of a Knudsen micro-pump (see Figure 7), researchers built the pump using clinoptilolite, a nanoporous mineral. The pump was able to produce gas flow rates up to 6.6 $\times 10^{-3}$ cubic cm/min with an input power of less than 300 mW/cm^2 [64]. The average adult human breathes air at a rate of about 8 litres, or 8,000 cubic centimetres, per minute. Scaling the lung dimension down by a factor of about 140 leads to a required breathing rate of about 2.8 x 10^{-3} cubic centimetres of air per minute. The Knudsen compressor detailed in Ref. [64] would be able to meet this required air pumping rate.

JULY 2018
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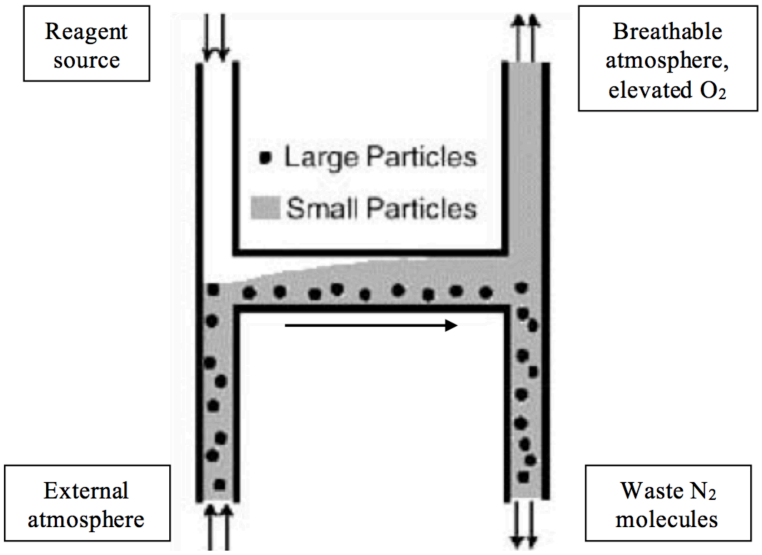

Figure 8: Schematic of an H-filter. On the left, a reagent is fed into the top of the channel and a sample fluid containing large and small molecules is fed into the bottom of the channel. Both streams pass into the centre channel and flow from left to right. Because of the faster diffusion times of the small molecules, they diffuse into the reagent and exit at the top right channel while the large molecules stay in the sample fluid and exit through the bottom right channel. Reproduced from Ref. [65].

In terms of the molecular filter in the suits, a number of techniques are available for separating molecules at the microscale (see Ref. [68] for an overview of classic techniques in chemistry). For instance, the H-filter is a relatively new microscale molecular filter based on diffusion [65]. It works by running two fluid streams parallel to each other. Figure 8 shows how the streams flow from left to right across the horizontal "bar" of the H. No mixing occurs across the two streams since the microscale flow is not turbulent. The only transport of molecules across the streams is by molecular diffusion. In Figure 8, the small molecules diffuse quickly from a sample stream (for example, a sample taken from the external atmosphere) into the reagent stream (for example, air that is low in oxygen content), while very large molecules will remain indefinitely in the sample stream because of their much larger size and much decreased diffusion rate [65]. An H-filter could be used to filter some of the slightly smaller (relative to nitrogen molecules) oxygen molecules from one air supply and add them to a second air supply in Ant-Man and the Wasp's suits, thus elevating the relative oxygen levels of the second air supply. This oxygen could then be used for respiration after being compressed and reduced in size using Pym particles.

The microfluidic technology elements discussed above: the Knudsen pump and the H-filter, along with microfluidic compressor and Pym particle technology elements, could be embedded in Ant-Man and the Wasp's suits in the way depicted in Figure 9. The tank on Ant-Man's back (outlined in red) could be the first air supply. In the tank, air could be drawn in from outside Ant-Man's suit using a Knudsen pump, and shrunk using Pym particles. The air could then be compressed in the tank using a microscale compressor and pumped up to Ant-Man's mask through internal or external tubing (outlined in blue). (In the 2015 film *Ant-Man*, the tubing is external. In the 2016 film *Captain America: Civil War* and in the 2018 film *Ant-Man*

JULY 2018
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and the Wasp, the tubing is no longer visible, and has presumably been re-routed inside the updated suit. See, e.g., Figure 1.) The air intake at the mouth outlined in green could be a second air supply used to supplement the oxygen levels of the first air supply. Here too, the air would need to be drawn into the suit (perhaps using pressure differentials caused by Lang's and Van Dyne's natural respiratory mechanics, or perhaps using a Knudsen pump), shrunk using Pym particles, and compressed. The two air supplies could then be brought together through an H-filter placed directly behind the mouth air intake, and the resulting air supply would have the elevated oxygen levels Lang and Van Dyne need to compensate for the 100-fold increase in their metabolic rates per unit mass.

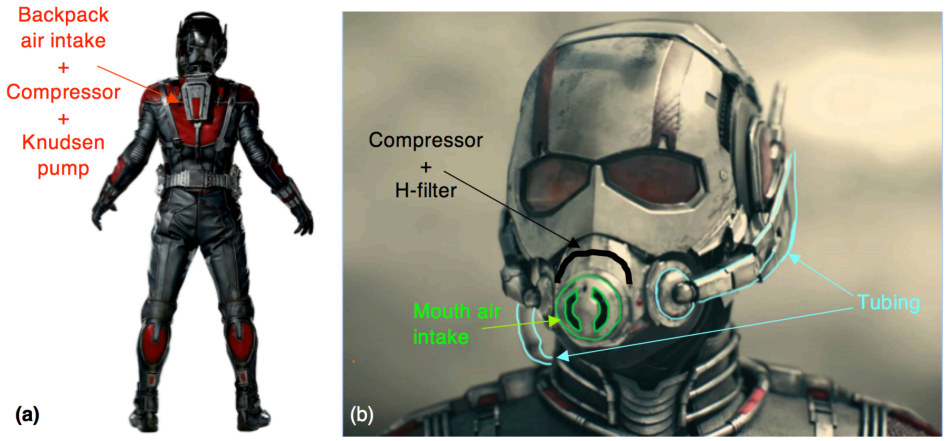

Figure 9: Microfluidic technology integration into the Ant-Man suit. Ant-Man's suit from the 2015 film [5] has a backpack unit connected to the mask with tubing. (a) Back view [69]. (b) Front view. The backpack could be the first air intake and supply. The tubing, outlined in blue, could connect the air from the first supply to the second supply, and the mouth intake, outlined in green, could be the second air supply. These components, together with Pym particle, microscale compressor, Knudsen pump, and H-filter microfluidic technologies, could provide Ant-Man and the Wasp with a compressed air supply containing elevated O_2 levels in order to overcome the 100-fold increase in metabolic needs per unit mass and the "death zone dilemma" they face at the microscale.

CONCLUSION

While Pym particles provide a fictional mechanism by which mass can be manipulated, and object sizes altered at will, the limitations of realistic human biochemistry remains a significant obstacle for both Ant-Man and the Wasp. Human physiology has evolved to operate efficiently at the macroscale, and the principles on which the human respiratory, circulatory, and other physiological systems operate do not work efficiently at the microscale. This leads to a multitude of problems, such as a significantly increased metabolic demand per unit mass and entering the "death zone." The latter can develop when Ant-Man and the Wasp shrink to the microscale and the effective atmospheric density and pressure in the suits is as if they are nearing the top of Mt. Everest. There are many other potential issues not discussed here, such as the vasculature in Lang and Van Dyne's bodies becoming nanoscale when they shrink in their suits, thus leading to special nanofluidic challenges in their cardiovascular systems, like quantum mechanics effects and low mass effects. However, the basic challenges of humans breathing at the microscale can, as we have shown, potentially be addressed using

JULY 2018
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current microfluidic technologies, such as Knudsen pumps and H-filters. These technologies could help to bridge the gap between insect and human physiology, allowing for, with a little suspension of disbelief, Ant-Man and the Wasp to successfully save the day.

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APPENDIX

Here, we reproduce the MATLAB code used to estimate the apparent atmospheric density that Scott Lang and Hope Van Dyne experience when the shrink to the size of an insect. The calculations assume air is an ideal gas.

```
clc; clear variables; close all;

Rho0=1.225; % density of atmosphere at sea level (kg/m^3)

langFull=1.8; % rounding Scott Lang's height

langReduced=langFull/141.73; % approximate size reduction (1.8m to 0.0127 m). Assumes 0.5 inch height.

%% Assume cube equal to Scott's full height to get total air mass.

atmoFull=Rho0*langFull^3;

%% Assume cube equal to Scott's reduced height to get reduced air mass.

atmoReduced=Rho0*langReduced^3;

%% Calculation of subjective atmospheric density

rhoSubj=atmoReduced/(langFull^3); % reduced mass at subjective full size

%% Atmospheric constants (assuming sea level, room temperature, etc.)

p0=101.325; % kPa, sea level

T0=288.15; % K, room temp

g=9.80665; % m/s^2, gravity at sea level

L=0.0065; % K/m, temperature lapse rate

R=8.31447; % J/(mol*K), universal gas constant

M=0.289644; % kg/mol, molar mass of dry air

h=1:18000; % Height, starting at 1 meter.

%% Preallocation

Pressure=zeros(1,1800);

rhoHeight=Pressure;

alt=0;

%% Calculation

for i=1:18000 % assume max height 18 km

    alt=alt+1;

    Pressure(i)=p0*(1-L*alt/T0)^((g*M)/(R*L));

     T=T0-L*alt; % temperature at some altitude (only valid inside troposphere, average max of 18km)

    rhoHeight(i)=Pressure(i)*M/(R*T);

end

%% Locating matching atmospheric conditions

for i=2:length(rhoHeight)

    if rhoHeight(i)<=rhoSubj

        Loc=i;

% disp(Loc)

%  disp(Pressure(Loc))

        break

    end

end
```

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