Micropumps Overview

Primary Knowledge Unit
Participant Guide

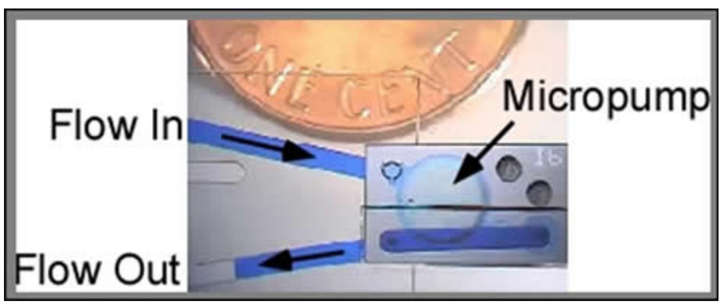
Description and Estimated Time to Complete

This learning module introduces the micropump, how it works and where it is used in microtechnology. Activities allow for further discovery into the operation of micropumps.

This unit introduces you to the types and operations of micro and nano-sized pumps, their applications, and their differences and similarities with macro-sized pumps.

Estimated Time to Complete
Allow approximately 20 minutes to read through this unit.

Introduction



An example of a micropump. Debiotech's Insulin Nanopump^{TM} is used to deliver insulin to diabetic patients. The blue fluid is being pumped. (Image courtesy of Debiotech S. A.)

Micropumps are scaled down versions of everyday macroscopic pumps (e.g., water pumps, fuel pumps). They have dimensions in the microrange (1×10^{-6}) which means that these micropumps or devices within the pumps are as small or smaller than the diameter of a strand of hair (60 to 100 micrometers). Micropumps are typically used to move a liquid or gas (fluid) from one location to another. Inkjet printers, blood analyzers, and implantable insulin delivery systems are a few examples of where micropumps are currently used.

Did you know that a vacuum cleaner is a pump? It moves air (and dirt) from one location to another (the carpet to the bag); therefore, it is a pump. Another pump you may be familiar with is a well water pump which is used to extract water from under the ground. And who hasn't filled up a bicycle tire or a tire of an automobile with an air pump? All of these pumps have moving mechanical moving parts and thus are considered mechanical pumps, the most common macro-sized pump.

Like their macro-size equivalents, micropumps are also designed to move fluids; but because of their considerably smaller size, they can also pump fluids using non-mechanical methods that exploit the physical characteristics of fluids at the micro-scale. With this in mind, micropumps are divided into two main categories: mechanical micropumps (those with moving parts) and non-mechanical micropumps (those without moving parts).

Micropumps are being developed for many reasons. Two primary reasons are reduction of weight and the ability to manipulate small volumes. Because of their reduced dimensions, micropumps weigh less and use less space than their macroscopic counterparts. They also have the ability to handle extremely small volumes of liquid very efficiently. The medical industry is taking advantage of these characteristics. A small drop of blood (rather than a vial of blood) can be extracted from a patient and distributed on a chip for analysis by using a micropump. Micropumps are also being developed that can be used in vivo or internal to the pump. These pumps could be used to deliver medications for a variety of purposes.

This unit introduces different types of micropumps and several of their applications.

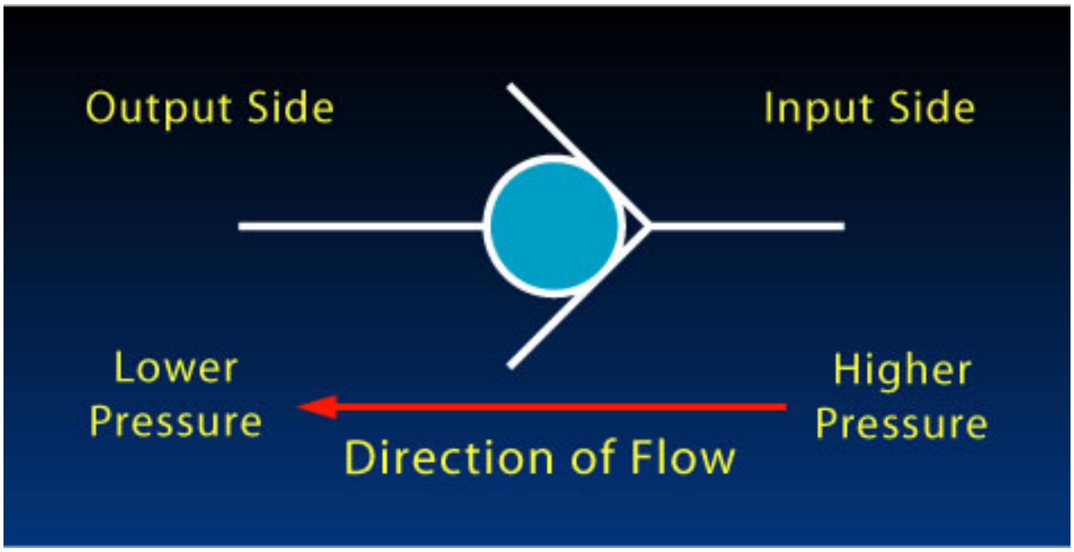
Objectives

- Describe how mechanical micropumps work and discuss an application.
- Describe how non-Mechanical micropumps work and discuss an application.

Terminology (A glossary is provided at the end of this unit)

Bubblejet printing
Insulin
Lab on a chip (LOC)
Macroscopic
Microchannel
Micropump
Micron
Raster
Viscosity

What is a Pump?



Check Valve

In order to understand a micropump, the first step is to understand its macroscopic cousin. Simply stated, a pump moves fluids (liquids or gases) from one place to another. Fluids move or flow when there is a region of high pressure and a region of low pressure. Specifically, fluids move from a higher pressure to a lower pressure. Flow of the fluid continues until the pressure is equalized.

In order to understand how fluids flow from a high to a low pressure, consider a bottle of soda. Bottling plants package their sodas under pressure in order keep them at the proper level of carbonation (dissolved CO_2). Therefore, the pressure inside soda cans or bottles is higher than that of the surrounding atmosphere. When a bottle of soda is opened, there is a rush of gas (the escaping CO_2) from the bottle. The CO_2 is moving from the higher pressure inside the bottle to the lower pressure of the atmosphere.

Pumps operate by increasing or decreasing a fluid's pressure causing it to flow. A good example is a bicycle pump. Bicycle pumps are "check-valve" pumps. Check-valves are valves that allow flow in only one direction. (*See figure of check valve*) Flow is allowed only from the input to the output and is blocked if fluid tries to flow in the opposite direction.

Bicycle Pump Example

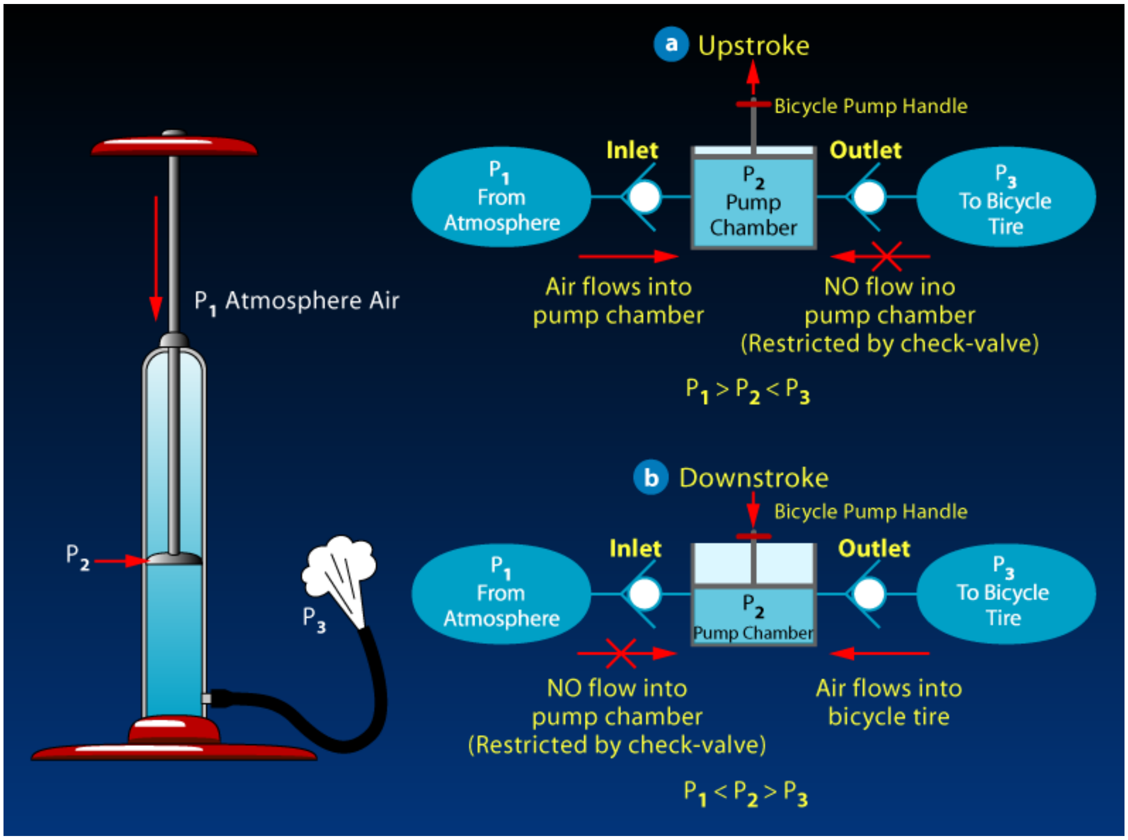


Diagram of a Bicycle Pump

Bicycle pumps operate using energy input by the operator. The operator moves the handle of the pump up and down which moves the pump's piston up and down. Referring to the diagram of a bicycle pump, the up-stroke draws air into the pump chamber while the downstroke pushes air into the tire.

On the upstroke (a), a low pressure (P_2) is created in the pump chamber drawing higher pressure (P_1) air through the inlet check-valve.

On the down-stroke (b), the pressure of the air in the pump chamber (P_2) increases, driving high pressure air through the outlet valve and into the tire (P_3).

Types of Micropumps

Mechanical Micropumps	Non-Mechanical Micropumps
Check-Valve Pumps	Ultrasonic Pumps
Peristaltic Pumps	Electrohydrodynamic Pumps
Valveless Rectification Pumps	Electrokinetic Pumps
Rotary Pumps	Phase Transfer Pumps
	Electro Wetting Pumps
	Electrochemical Pumps
	Magetohydrodynamic Pumps

Types of Micropumps

Micropumps can be broken down into two subcategories: mechanical and non-mechanical micropumps. Mechanical micropumps have moving parts while non-mechanical micropumps do not. Most mechanical micropumps are literally scaled down versions of their macroscopic counterparts. Non-mechanical pumps are typically not found in the macroscopic world; however, non-mechanical micropumps are commonly used in micro devices because they can take advantage of some of the physical properties of fluids when the volumes decrease to the micro-size and smaller. There are several different types of micropumps in each of these two categories. A summary of the two designs is shown in the table. Both categories of micropumps are used in a wide range of applications, such as biomedical, microelectronics, consumer products, and printing.

In the following sections, mechanical and non-mechanical micropumps are discussed in more detail.

Question

Is a bicycle pump a mechanical or non-mechanical pump? Why?

Mechanical Micropumps

Mechanical micropumps are smaller versions of macroscopic mechanical pumps. They have moving parts that create a higher pressure in the fluid contained within the pump, subsequently causing the fluid to flow.

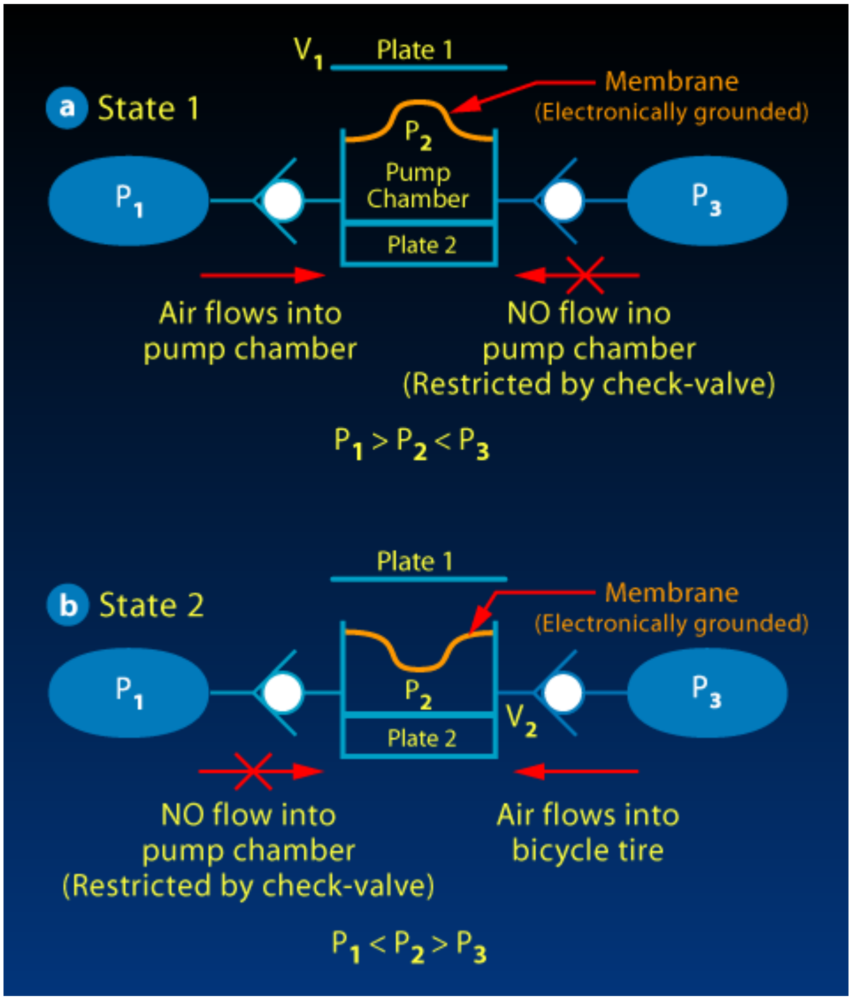
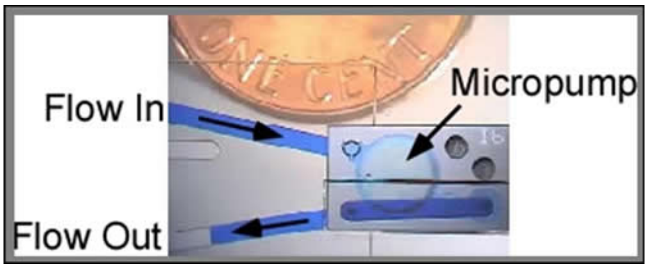
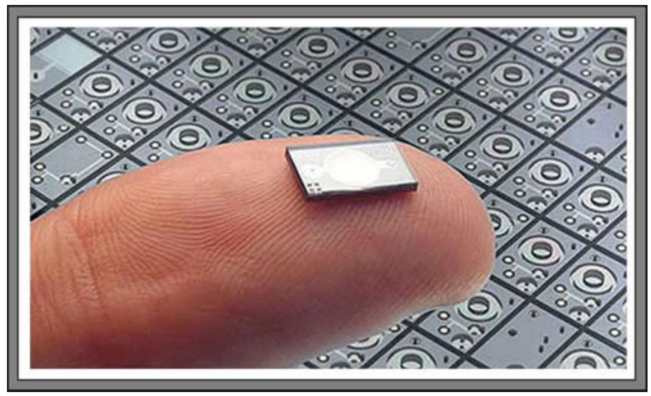


Diagram Depicting the Operation of a Diaphragm Micropump

A common type of mechanical micropump is the diaphragm pump. A description of its macroscopic counterpart was given in a previous section with the bicycle pump. In the micropump version (see diagram above), a thin membrane or diaphragm (1 micrometer thick) is used in place of the piston in the bicycle pump. The effect of the membrane moving up or down is that either a relatively low or high pressure develops in the pump chamber. An upward movement of the membrane from a non-deformed position (state 1) creates a low pressure in the pump chamber, (P_2). P_2 becomes less than the inlet pressure (P_1). Movement of the membrane from state 1 to state 2 increases the pressure in the pump chamber to a pressure greater than or equal to the outlet pressure (P_3).

An actuator moves the membrane between states 1 and 2. There are many different types of actuators for these pumps. One popular type is the electrostatic actuator. This actuator uses an electric field to move the membrane between states 1 and 2. This is accomplished by applying a voltage to either plate 1 or plate 2. The membrane is electrically grounded. With the membrane electrically grounded and a voltage applied to plate 1 (no voltage on plate 2), the membrane moves closer to the energized electrode (state 1). When a voltage is applied to plate 2 (no voltage on plate 1), the membrane moves closer to plate 2 (state 2). As the membrane oscillates between these two states, fluid is moved from the pump's input to its output. In addition to assisting in the changes of pressure in the pump chamber, the check valves also prevent fluid from flowing in the opposite direction.



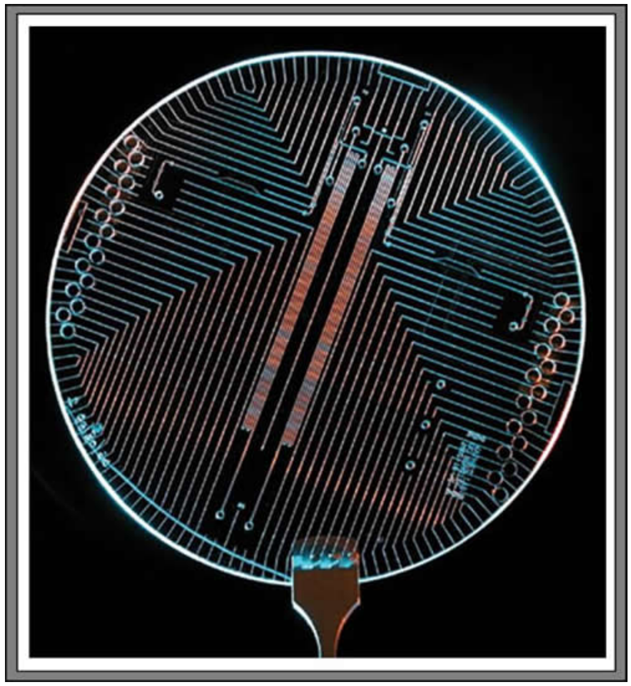


Insulin Micropump (Image courtesy of Debiotech, S. A., Switzerland)

One application of a mechanical diaphragm micropump is for delivery of insulin to diabetes patients for the purpose of regulating their blood sugar. The figures show an insulin micropump developed by Debiotech. "The working principle is a volumetric membrane pump, with a pair of check valves, integrated in a MEMS chip. The chip is a stack of 3 layers bonded together: a silicon on insulator (SOI) plate with micromachined pump-structures and two Pyrex cover plates with through-holes. This MEMS chip is assembled with a piezoelectric actuator that moves the membrane in a reciprocating movement to compress and decompress the fluid in the pumping chamber."[1]

The reciprocating motion of the membrane moves the liquid in pulses. Each pulse is approximately 0.2 microliters, only 0.00001% of a 2 liter bottle. Yet, the insulin is so potent that 0.2 microliters is all a patient may need to regulate blood sugar. Because of its small size, this micropump can be mounted on a small arm patch to accurately distribute precise amounts of insulin when needed. An implantable device with a minimum dosage of 150 nanoliters is currently under development.[2] Such a device will prove invaluable for not only the precise control of diabetes, but for pain management and a wide range of conditions.

Lab on Chip (LOC)



Lab on a Chip or LOC (Image courtesy of Mathies Lab, UC Berkeley)

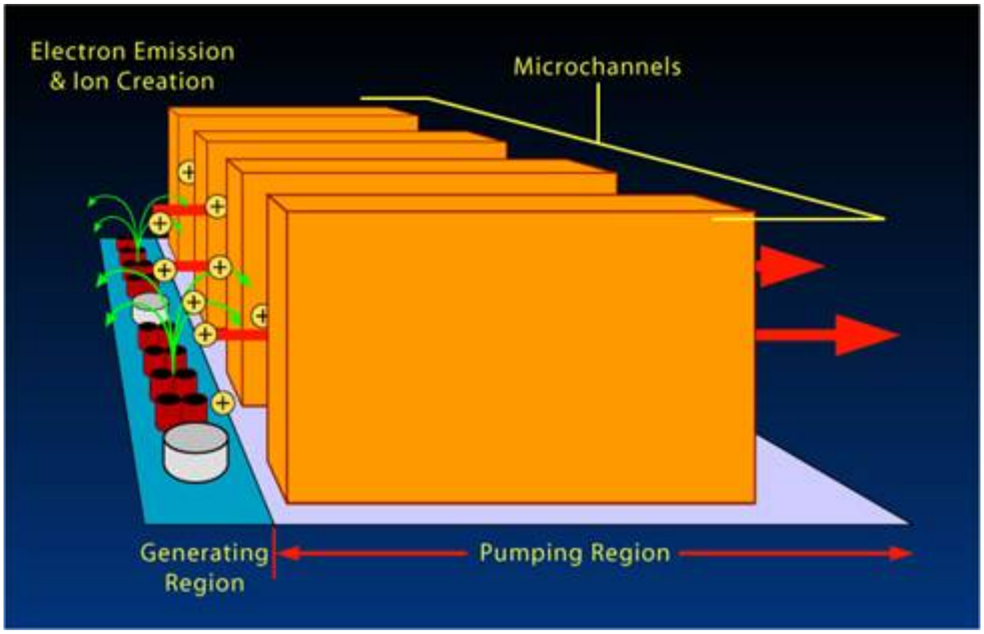
Another biomedical application for a mechanical micropump is the "Lab on a chip" (LOC). In MEMS technology, LOC refers to a chip on which several laboratory functions have been integrated. LOCs are typically only a few square millimeters or centimeters in size. They handle extremely small fluid volumes (picoliters or less). Micropumps are used to remove a drop of blood from a patient and distribute it onto the LOC. Once on the chip, the movement of the blood through the various channels is controlled using a variety of techniques: electroosmotic flow (applied voltage), “pressure-driven flow, centrifugal pumping, electrochemical bubble generation, fraction collection, capillary forces, laminar flow and gradient concentration generation”.[3]

The photograph shows a LOC that is designed to sequence large genomes quickly and cost effectively. This chip could potentially provide information leading to medical care tailored to a patient's specific genome.

Non-Mechanical Micropumps

Non-mechanical micropumps make use of the physical properties of fluids that can best be utilized when operating in the microscale or smaller. This type of pump causes movement of the fluid by means other than those created by moving mechanical parts. Electric fields, magnets, and heat can all be used to cause movement.

Ion-Driven Airflow Micropump



Theoretical Diagram of a Microscale Ion Driven Airflow Micropump

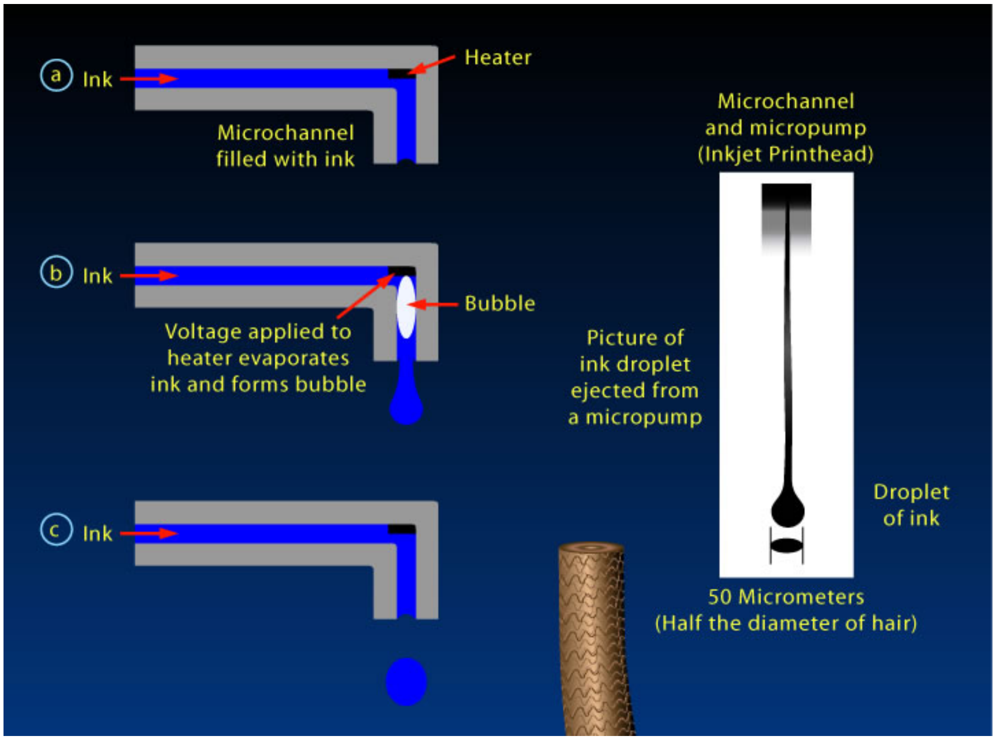
(Technology being developed by Thorn Technologies)

Non-mechanical micropumps are used in the microelectronics industry to cool microchips. The build-up of heat in microelectronic chips causes a decrease in performance (slower processing speeds); therefore, it is necessary to cool the chips with air flow since liquid is not a feasible option. An example of an airflow cooling micropump is illustrated in the graphic above. This non-mechanical micropump cools microchips using a technique dubbed "Microscale Ion Driven Air Flow". As illustrated in the diagram, ions are generated in the surrounding air through collisions with electrons that have been emitted from a bank of "cold-cathode electron emitters". This process is similar to the corona wind concept except that it is accomplished at lower voltages. "The ions are moved by a series of microfabricated electrodes that generate strong electric fields to pump ions through air."[4]

Inkjet Printers

A common application of micropumps is in inkjet printing. Inkjet printheads are actually an array of micropumps used to deliver small volumes of liquid (approximately a picoliter) onto paper to create images and text. Both mechanical and non-mechanical versions of inkjet micropumps are currently in production. Let's take a look at a couple of non-mechanical micropumps - the bubble-jet printhead and the piezoelectric printhead.

BubbleJet Printers



The Micropump in a Bubblejet Printer Head and

actual ink droplet from a micropump

Non-mechanical micropumps are used every day in businesses and home offices in inkjet printers. One type of inkjet printer uses a phase transfer pump. In this pump, heat is applied locally to a microchannel filled with ink. Very quickly (0.0001 seconds) the ink evaporates forming a bubble. The bubble forces a tiny droplet of ink out of the microchannel and onto the paper below. It is because of this bubble that Cannon Inc. has named its printer line BubbleJet. Hewlett-Packard has developed similar technology and is calling it “thermal inkjet”.[5]

Referring to the diagram above, the process of pumping a droplet of ink from BubbleJet micropump is a multiple stage process.

(a) The microchannel is filled with ink. Because the microchannel’s dimensions are so small (approximately a micrometer) the liquid automatically fills the microchannel due to the surface tension of the liquid and the adhesive forces between the liquid and the walls of the microchannel. This effect is called capillary action.

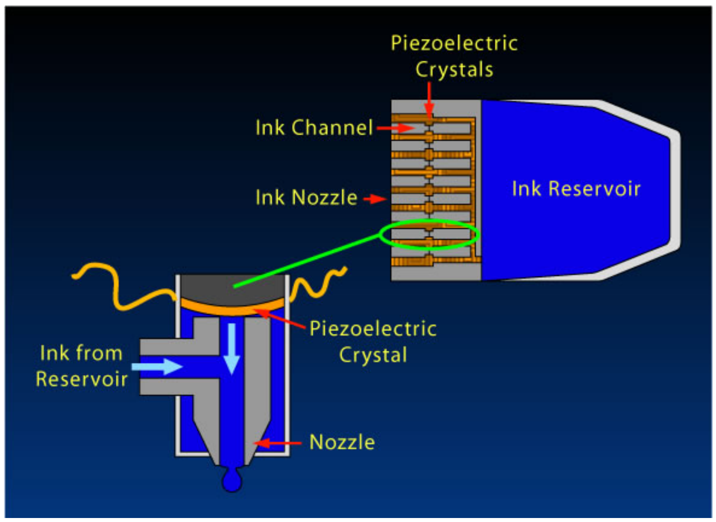
(b) Next, an electrical voltage is applied to the heater. Current through the heater creates enough heat energy to evaporate the ink in less than 0.0001 seconds. Evaporation of the ink forms a void or bubble. The bubble immediately forces the ink below it out of the channel.

(c) The ink falls onto the paper below, collapsing the bubble. The voltage is removed and the heater turns off. The microchannel automatically refills due to capillary action.

This process happens in approximately 0.0001 seconds. Therefore, these micropumps are capable of delivering approximately 10,000 drops per second. A printhead consists of several of these micropumps arranged in an array. The printhead then rasters back and forth dropping about 10,000 picoliter size droplets from each pump, every second. This enables the printing of several pages of text in one minute.

Question: *What is the property of liquid that retains the water in your toothbrush to the point that you need to shake it out rather than turn the brush over and let the water run out?*

Piezoelectric Inkjet Printing



Piezoelectric Inkjet Printhead

Another type of inkjet printhead uses piezoelectric crystals to initiate the pumping action of the micropump. As seen in the figure, an ink reservoir is located behind the ink channels. Piezocrystals are located between the channels and the reservoir. To emit ink through a microchannel, a small alternating electric charge is applied to a crystal causing the crystal to vibrate. As part of the vibration, the crystal contracts forcing a minute amount of ink out of the nozzle. When the crystal relaxes during the vibration, ink is pulled from the reservoir due to capillary action into the ink microchannel.

Just like in the bubblejet, each printhead contains and array of micropumps enabling the ability to deposit thousands of drops of ink every second on the page. Difference models of printers provide the consumer with choices in the speed of the printing as well as the resolution (dots per square inch or dpi).

Applications of Micropumps[7]

Micropumps are currently used in a wide range of industries such as automotive, aerospace, biomedical, chemical processing and food and beverage. They are used for many different functions:

- circulate fluids
- transfer fluids from one point to another
- meter fluid amounts and dosages
- heating and cooling applications
- mixing minute amount of fluids
- dispensing precise dosages of medications,
- prepare samples for medical diagnoses and therapeutics
- safe handling of hazardous fluid and waste extraction

The benefits of micropumps are many:

- Continuous or pulsed flow – depending on applications
- Long life
- Miniaturization minimizes leak potential
- Ideal for hazardous environments
- Low power consumption
- Precise distribution and dosages
- Fast dynamic response

Summary

The two main classes of micropumps are mechanical and non-mechanical. Mechanical micropumps have moving parts that cause movement of a liquid or gas from one location to another. Non-mechanical pumps have no moving parts and make use of other physical phenomena (such as the properties of fluids) that can only be utilized by micropumps because of their small size.

Micropumps are used in a variety of industries from automotive to medical. Applications range from fuel injection to insulin injection and cooling to hazardous waste distribution.

Food for Thought

a. Why use a micropump instead of its macroscale counterpart for delivery of insulin in diabetic patients?

b. How are membranes used to pump fluids?

References (You may need to copy and paste URLs)

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[5] "Inkjet and BubbleJet Printer Technology". MicroMechanics. http://mimech.com/printers/inkjet-printer-technology.asp

[6] Kowalski, K.M., Bottled Bubbles.(how carbonated beverages are made and why they produce bubbles). Odyssey, 2001. 10(6): p. 12-13.

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[8] Nguyen, N.-T., X. Huang, and T.K. Chuan, MEMS-Micropumps: A Review. Journal of Fluids Engineering, 2002. 124: p. 384-392.

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[10] Tseng, F.-G., C.-J. Kim, and C.-M. Ho, A Microinjector Free of Satellite Drops and Characterization of the Ejected Droplets, in 1998 ASME International Mechanical Engineering Congress and Expositions. 1998: Anaheim, CA. p. 89-95.

[11] Microscale Ion Driven AirFlow Pump http://www.nsf.gov/news/mmg/media/images/pr04039garimel_nanol_f.jpg

[12] Introduction to Lab-On-A-Chip 2015: Review, History and Future. Elveflow: Plug & Play MicroFluidic. Microfluidics Tutorials. http://bit.ly/1PVjW1k

Glossary

Bubblejet printing – a method using a non-mechanical micropump to transfer ink onto paper

Insulin – a substance (usually a liquid) used in the treatment of diabetes that restores the body's ability to regulate sugars and other carbohydrates

Lab on a chip (LOC) – a common term used in the MEMS industry that refers to a chip on which several functions of a laboratory have been integrated. LOCs are typically only a few square millimeters or centimeters in size and handle extremely small fluid volumes (typically picoliters or less).

Macroscopic – something that is able to be fully perceived by the naked eye

Microchannel – a channel with cross-sectional dimensions in the micrometers (µm) (between 100 µm and 1 µm), typically used for moving liquids and gases.

Micropump – a scaled down version of a pump, with dimensions in the microrange

Micron – alternative name for micrometer

Raster – to move back and forth

Viscosity – a measure of a fluid's resistance to flow (e.g., water has a relatively low viscosity and honey has an extremely high viscosity)

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