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WO 2012/168181 A1 **US 20110198321 A1**
US 20050006359 A1

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Other: **EPODOC, WPI**

(54) Title of the Invention: **A Method of forming a perforate membrane and an ultrasonic atomiser using the perforate membrane**
Abstract Title: **Forming a perforate membrane by laser and reaming**

(57) A method of forming a perforate membrane 70 for use in an ultrasonic atomiser is disclosed. The membrane is formed by applying pulsed and focussed laser energy to the membrane and changing the focus and/or energy of the laser after each pulse or a number of pulses in order to reduce the taper of the perforations 22 as they pass through the membrane (figures 1). The perforations are then reamed by abrasion in order to create nozzles with a number of distinct sections (figures 2 and 3). The diameter of the reamer 30 is chosen to remove recast melt from the interior of the nozzles leaving them smooth. The reaming is controlled to ensure the smallest diameter sections of the nozzles are the shortest in length (figure 3c).

FIG 3 (a)

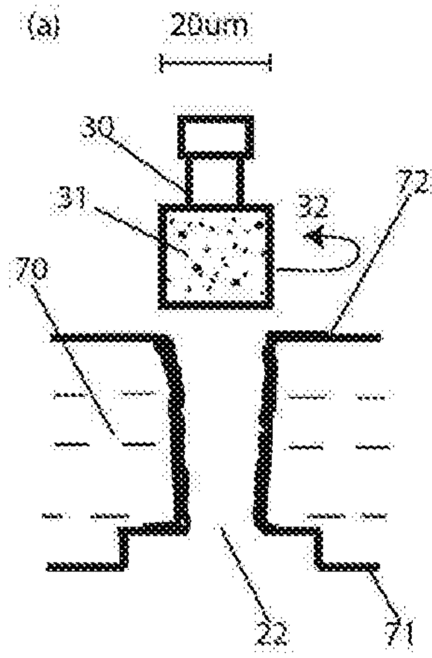

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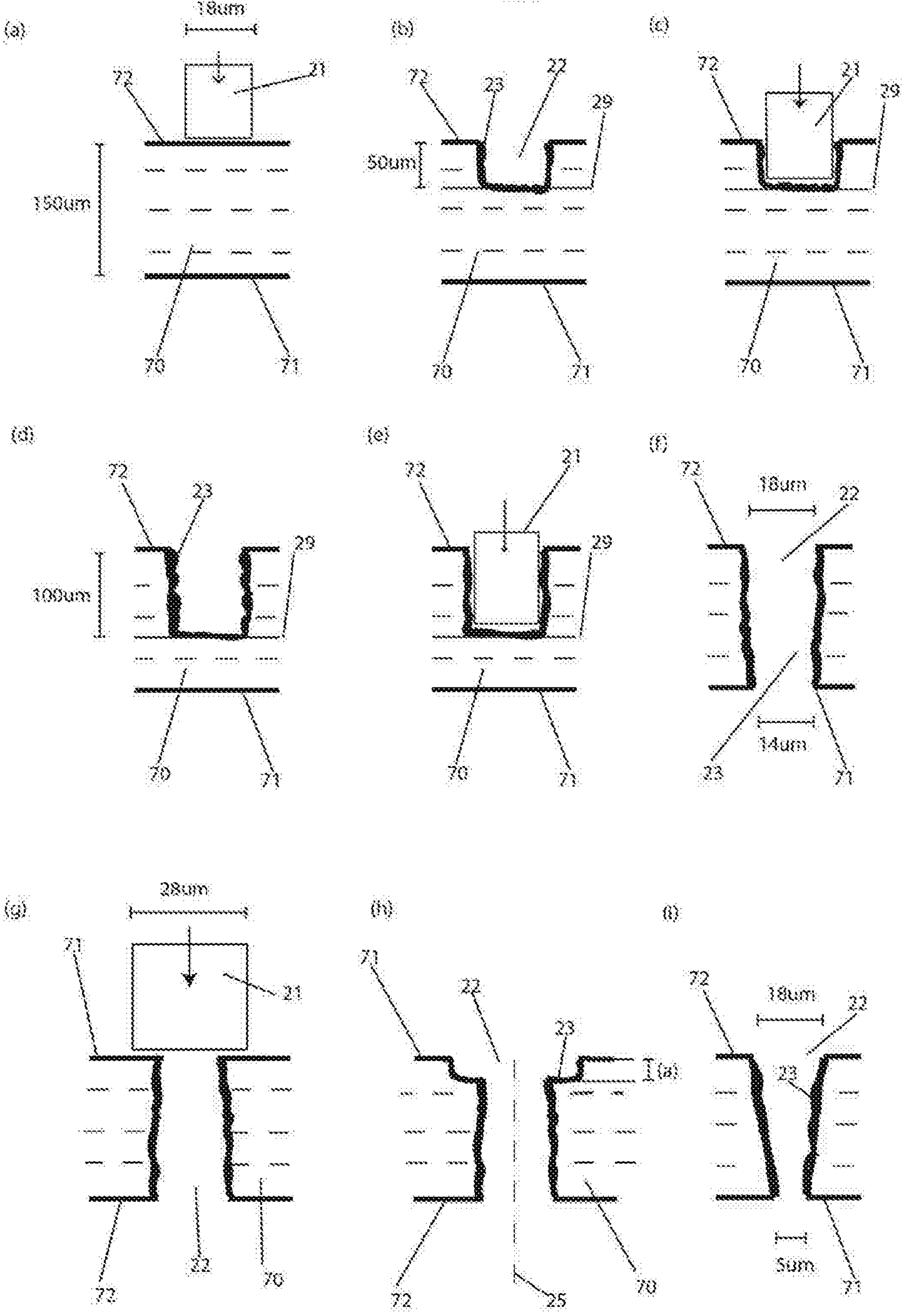
FIG 1


(a)
18um
72
21
150um
70
71
(b)
72
23
22
29
50um
70
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(c)
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29
70
71
(d)
72
23
29
100um
70
71
(e)
72
21
29
70
71
(f)
72
18um
22
23
14um
71
(g)
28um
71
21
72
22
70
(h)
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22
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(a)
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25
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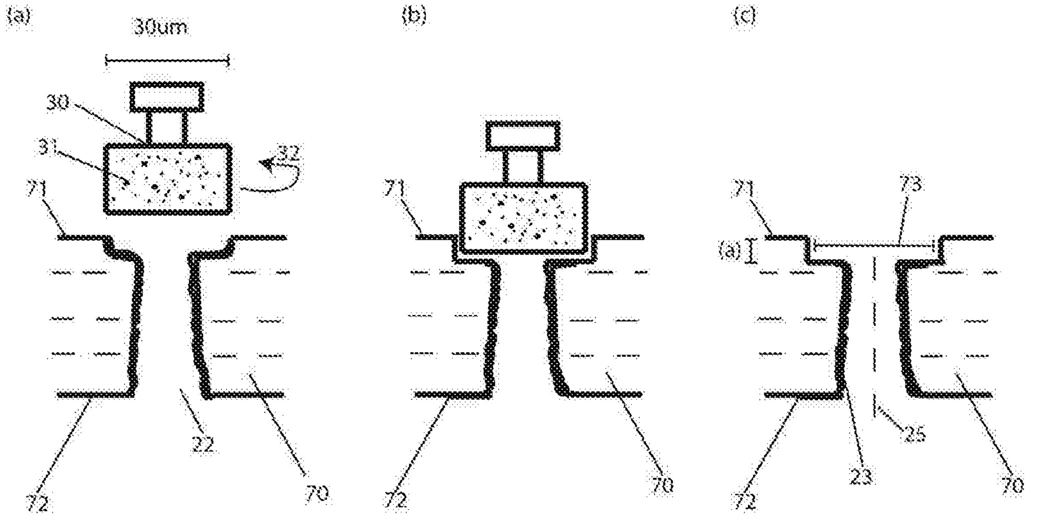
(i)
72
18um
22
23
5um
71

FIG 2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(b)
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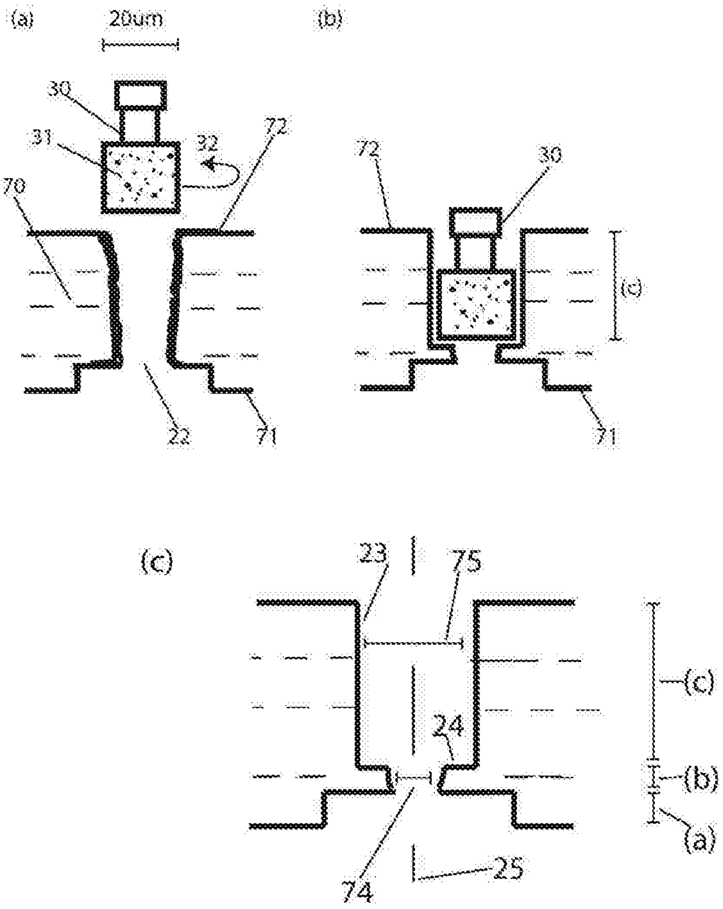
23
70

FIG 3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(b)
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(c)
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(c)
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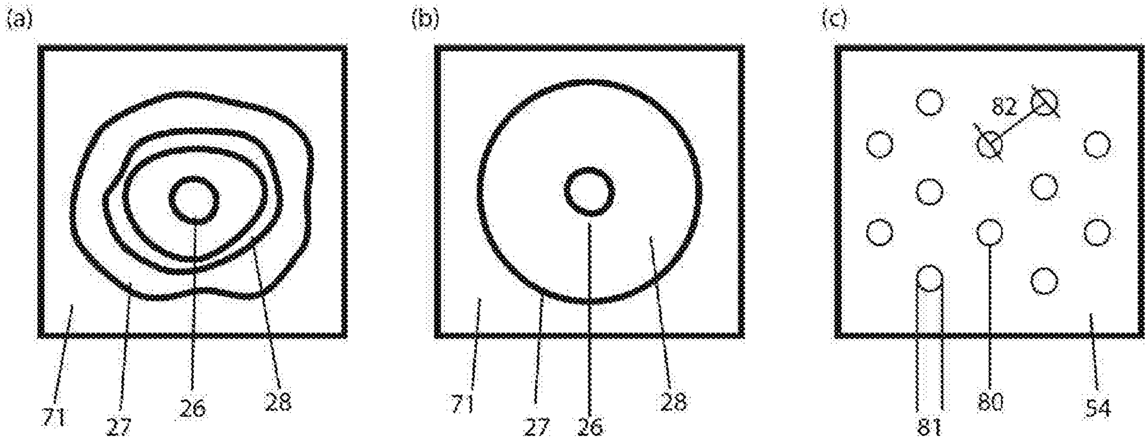
75
24
(c)
(b)
(a)
74
25

FIG 4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(b)
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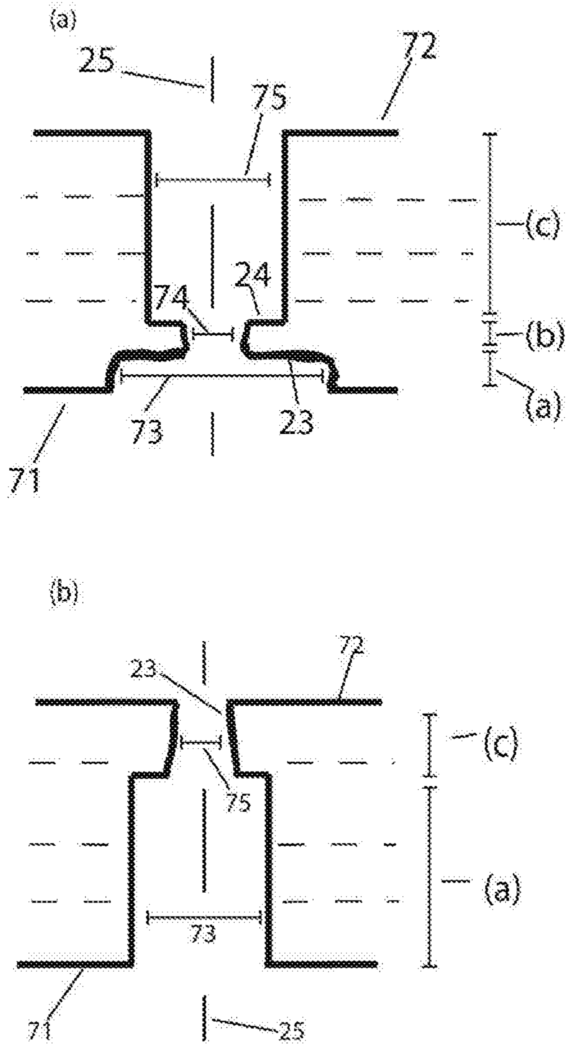
28
(c)
82
81
80
54

FIG 5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74
24
(c)
(b)
(a)
73
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71
(b)
72
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75
(c)
(a)
73
71
25

Fig 6

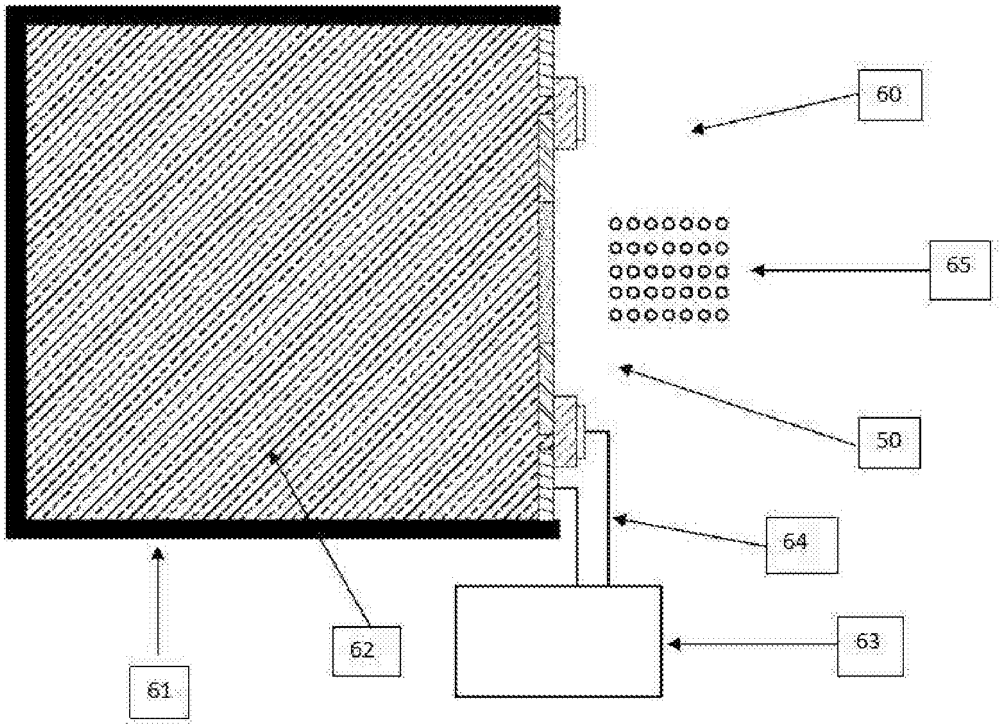


Fig 7

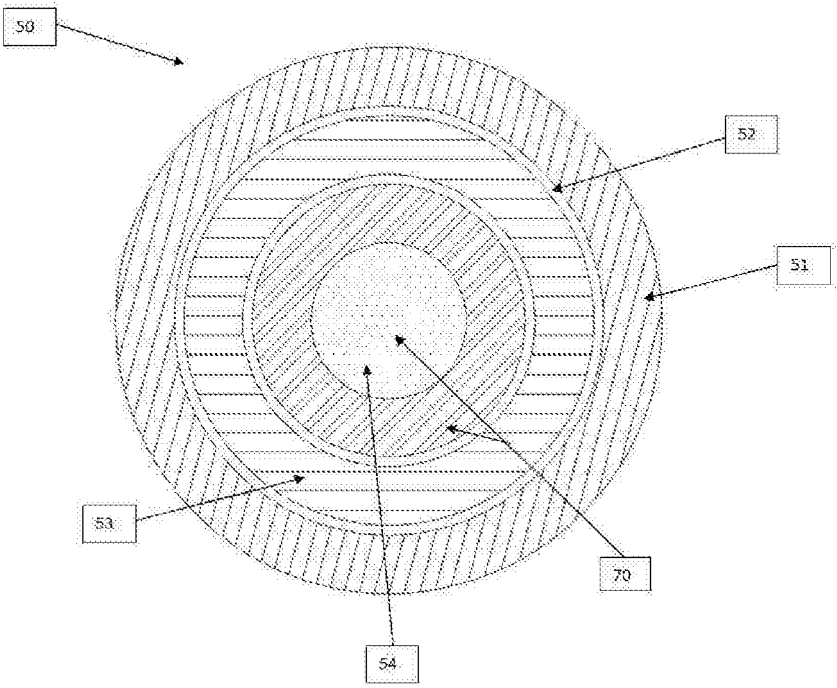


Fig 8

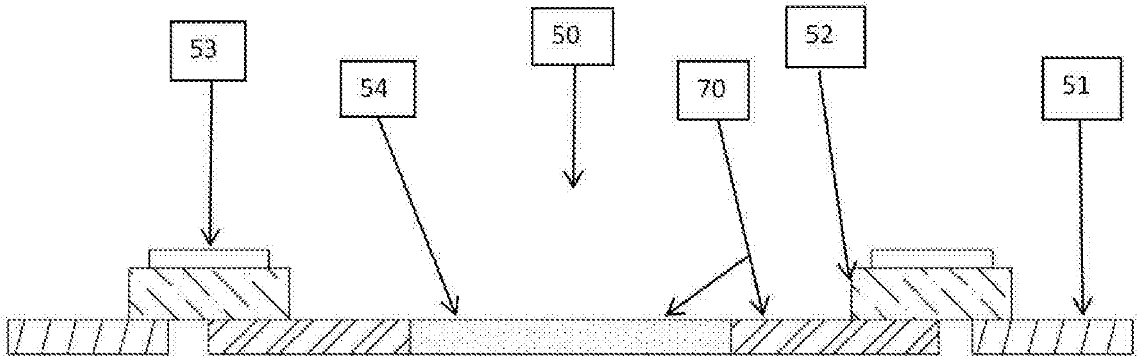
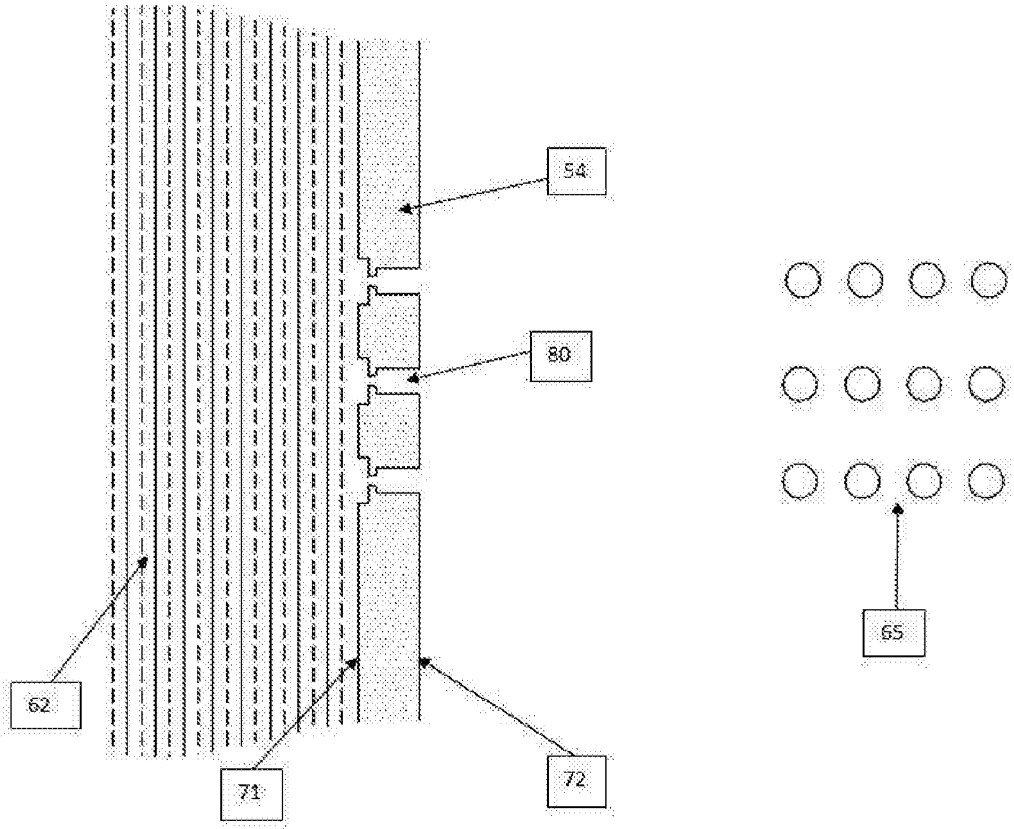


Fig 9



A METHOD OF FORMING A PERFORATE MEMBRANE AND AN ULTRASONIC ATOMISER USING THE PERFORATE MEMBRANE

Related art

Aerosol generating devices of the vibrating membrane type are well known, they contain a membrane that has a number of nozzles, a piezoelectric actuator and a drive circuit. The actuator when driven at resonance by the drive circuit will vibrate the membrane. Bulk liquid in contact with the first face of the membrane will be subjected to varying hydraulic pressure and is pumped into the nozzles. When the membrane's amplitude of vibration is sufficiently large droplets will be ejected from the opposite face of the membrane creating an aerosol mist.

Perforate membranes are typically made in a metal such as stainless steel and have nozzles created by a laser. Lasers do not produce a cylindrical hole in relatively hard metals, rather they are known to produce a 'tapered' hole whereby the entry hole has the largest cross sectional area and exit hole has the smallest cross sectional area. Therefore metallic membranes when in operation as part of an aerosol generation device fall into two broad categories. Firstly those that have a forward taper whereby the nozzles decrease in cross sectional area from the liquid entry side to the liquid exit side. And secondly those that have a reverse taper whereby nozzles increase in cross sectional area from the liquid entry side to the liquid exit side.

The patent EP1152836B1 illustrates how ultrasonic atomisation can take place with a reverse taper membrane, it explains how a new lower frequency regime can take place than with the more common forward taper devices. According to this new regime the following frequency to entry hole diameter relationship holds true:

$$f < [(8\pi s)/(27pq^3)]^{1/2}$$

The entry diameter of nozzles in the membrane = q
The liquid to be atomised having a surface tension = s
The liquid having a density = p
The vibration frequency of the membrane = f

Then the membrane is vibrated at the frequency f which is determined by the relationship so that droplets emerge from the exit surface with a diameter approximately equal to the diameter of the nozzle at the entry surface.

The patent is aimed at reducing the power consumption of a droplet generating device. The cost of droplet generator drive electronics is related to the frequency of operation, with higher frequencies associated with higher cost. The patent demonstrates how relatively large droplets can be produced at lower frequencies in comparison to a device containing a forward taper membrane. As the droplets are relatively large the device will spray the same amount of liquid as a similar forward taper membrane but at lower frequencies resulting in cheaper drive electronics.

The invention requires the liquid to be subjected to a pressure bias such that the pressure of the bulk liquid at the container side of the membrane is less than the pressure on the air side from which droplets emerge. However we have found that adding a pressure bias is unsatisfactory in operation. In particular as the container holding the liquid empties the pressure within the container changes, this causes an alteration in the spray rate of the atomiser for the same input of energy. Counteracting this pressure change is cumbersome adding to the complexity of the device and negating the value gained from cheaper drive electronics. It is consequently preferable to avoid using a pressure bias and alternate power saving methods found.

When spraying water at around 100KHz the equation noted above implies that there is a 40 micron entry hole diameter and exit hole greater than 40 microns. As the droplets are produced with a diameter approximately equal to the entry diameter of the nozzle the membrane can potentially produce droplets of 40 microns diameter at 100KHz. However with exit holes at or close to this diameter we have found that dripping becomes a problem. Liquid drips from the nozzles onto the surface of the membrane and is atomised from that surface, rather than directly from the nozzles themselves, this leads to uncontrolled droplet diameter. In our invention this circumstance is avoided by using smaller nozzles of below 40 microns entry diameter. However the smaller nozzle diameter is more difficult and expensive to produce.

The patent US7316067B2 discloses a perforate membrane and a technique to create it. The perforate membrane can be used in a forward or reverse taper configuration in an aerosol generating device and is created via laser drilling and a subsequent electropolishing technique. A two step laser drilling process is used to create perforations in the membrane that have a larger cross sectional area called the diverging portion and a smaller cross sectional area called the throat portion. In the first step percussion laser energy strikes the first face of the membrane but is turned off before it passes right through the membrane, thus creating the diverging portion. In the second step the focal length and/or the energy level of the laser is changed, then the laser is turned on again and drills right through the membrane. In this way a ledge inside the perforation is created at the intersection between the diverging and throat sections of the nozzle. The laser drilling process is also controlled to create a low friction nozzle, this is achieved by altering the power and/or the focal distance of the laser during the creation of either or both of the portions so that they are coated with a smooth recast melt layer. Upon completion of lasering the perforations are electropolished in order to make the nozzles smoother internally and reduce burrs in the drill area. As the diameter and length of the throat portion strongly affects droplet size the process is controlled so that the throat portion of the perforations is left unaffected by electropolishing thereby protecting them from variation. This low friction regime allows the passage of liquid through the nozzles with less energy than a membrane that is coarser.

A problem we have found with this technique is that even when recast melt is created in a controlled fashion and subsequently electropolished for the useful purpose of reducing friction and thereby power consumption it can still become dislodged from the nozzles. In the case of medical nebulisers the recast melt will contaminate medicine and this circumstance should be avoided. Therefore it is preferable for recast melt to be further removed rather than actively created.

A further problem is that the nozzle quality even after using this technique is still too low for those applications in which the visual impact of the aerosol mist is a factor. The quality of individual nozzles governs the distribution of droplet diameters in an aerosol mist, and even small variations in quality from one nozzle to the next, in particular of the cross sectional area of the throat section will produce a greater range of droplet sizes than is desirable. Passage of liquid through the nozzles is greatly affected by imperfections caused during the laser drilling process and a weakness in removing those imperfections with the subsequent electropolishing step. With a pulsed laser of the variety typically used to create nozzles in atomisers the imperfections regularly produced are broadly caused by recast melt and the tolerance of the laser itself. The recast melt can cause partial blockages, burrs on the surfaces of the membrane and a ripple or undulating surface through the nozzle. Typical laser drilling techniques have a tolerance of 2-3 microns, with an exit diameter of 100 microns this represents just a 2-3% error, however with an exit diameter of 20 microns the same error is 10-15%, the preferred embodiments for our invention is in this lower nozzle diameter region. A potential 15% variation will adversely affect the visual appeal of the mist with the greatest visual appeal from the lowest variation. A further electropolishing step is intended to improve the nozzle quality, the electropolishing as outlined lasts around two minutes however even with a high current density this will only remove a small amount of material, typically 0.2 microns. With an error of 2-3 microns from laser drilling the electropolishing does not substantially improve the nozzle quality. Electropolishing can be continued for longer than two minutes however in this circumstance warping starts to occur because the membranes are typically less than 200 microns in thickness and stresses inherent in the metal start to become apparent. Consequently laser drilling and subsequent electropolishing in the fashion disclosed does not provide an aerosol mist with droplets of sufficiently consistent size.

One of the aims of this patent is to reduce power consumption. When a perforate membrane is harmonically vibrated while in contact with a bulk liquid the liquid will enter the nozzles then pass through them and be ejected as droplets in a cyclic fashion. In reverse taper devices liquid enters the nozzles from the face with the smallest cross sectional area, in each cycle some of the liquid in the nozzles is displaced backwards towards the bulk liquid side before being pumped forward again, this wastes energy. In order to prevent the backwards flow of liquid inside the nozzle a ledge is produced at the interchange between the throat and diverging portions. To create the ledge a two step laser process is employed, the diverging portion of the nozzle is created first and then the focal length and/or energy of the laser is changed to create a narrower throat section. However this technique is adequate for this purpose only so long as the nozzles are relatively large. For example a membrane is 100 microns thick, laser energy is applied in pulses to create nozzles with a diverging portion of 100 microns diameter at the first surface and they taper to a diameter of 80 microns half way through the membrane before the laser is turned off. In the second stage the focal length of the laser is changed and the laser turned back on, a throat section of 40 microns diameter is put through the membrane. This will create a ledge that is 20 microns wide. However if the same membrane has a diverging portion with a diameter of 30 microns at the first face and tapers to a diameter of 26 microns half way through, then with a throat diameter of 20 microns, the ledge shrinks to 3 microns. As the laser is only accurate to 2-3 microns ledges cannot be created in this fashion for smaller nozzles.

The current invention

This patent concerns the creation of a membrane and the use of that membrane in an ultrasonic atomiser. In order to solve the problems outlined above a new technique to create nozzles is required. That technique is now discussed, it begins with a laser drilling process and progresses to a reaming process. The laser process drills a plurality of perforations in a membrane and then the reaming process hones the perforations into the desired nozzle geometry.

The reaming allows ledges to be created within the nozzles, recast melt to be removed from the nozzles and the quality of the nozzles to be optimised. The geometry in the nozzles is chosen to ensure that the smallest diameter section is not reamed and its length is minimised. The technique allows these features to be created in nozzles with exit and entry perforations below 40 microns diameter, which laser drilling alone would not allow. Upon creation of the membrane it is used in an ultrasonic atomiser. The atomiser allows relatively large droplets of liquid to be created in comparison to similar forward taper devices operating at the same frequency, with no dripping or pressure bias required.

Summary of the Manufacturing Technique

A summary of the technique to manufacture a nozzle to solve the outlined problems is now noted.

1) A membrane material with a given shape and thickness is chosen. A nozzle geometry is chosen to form a plurality of perforations through the membrane, each nozzle will have either two or three distinct but connected sections. Each section can have a different internal shape, depth and dimensions with the section with smallest diameter chosen also to be the shortest in length.
2a) Creation of two section nozzles. The membrane is placed into a pulsed and focussed laser machine so that the laser can drill through the membrane creating a number of

perforations. The power and/or focal distance of laser is changed after each pulse or a number of pulses so that the taper of the hole from the entry to exit is minimised.
2b) Creation of three section nozzles. The process in 2a) is carried out then the membrane is turned over, the laser is re-aligned to the centre of the nozzles and the beam diameter is changed. Each nozzle in the membrane is re-drilled to a depth less than the thickness of the membrane. The power and/or focal distance of the laser beam can be altered as in 2a) or left unchanged.
3a) The membrane is placed into a reaming machine, the reamer is a metal rod which has micron size diamond shards bonded to its exterior. The machine rotates the reamer at high revolutions and lowers it into a single section of each perforation with accurate computer controlled force and depth. The diamond shards remove material via abrasion and hone the perforations improving nozzle quality, removing recast melt and creating a ledge at the intersection between two sections. The diameter of the reamer is chosen to be the diameter of the hole plus twice Rp the maximum peak height of the recast melt.
3b) For a two section nozzle the reaming is carried out to a depth such that the reamed section is longer in length than the section left unreamed.
3c) For a three section nozzle either the entry section or both entry and exit sections are reamed, the middle section which is the smallest diameter section and remains unreamed is also the shortest in length of the three. Either the entry or exit sections can have the longer length. If both the entry and exit sections are reamed then between these two steps the membrane is turned over and the reamer diameter is changed.

For this technique there are three distinct nozzle geometries. The first uses four separate steps, this comprises two laser drilling steps with one drill on each surface of the membrane and two reaming steps with the liquid entry and droplet exit sections reamed once. The second geometry requires three steps, this involves two laser drilling steps one on each surface, plus reaming of the exit section from which droplets emerge. The third geometry involves two steps, a single laser drilling step and reaming of the entry section from which liquid enters.

Each distinct application will require nozzles with different features and the exact number of steps is the fewest that allow for the required nozzle features to be created. For example in this invention the created membrane could be used in a medical nebuliser and may need high hole quality to maintain droplet diameter in the range 4 microns thus allowing for proper ingestion of medicine into the lungs and most recast melt removed to prevent contamination of the medicine, in this case the nozzles could be laser drilled from both sides and reamed on the entry and exit sections for a total of 4 steps. As another example an atomiser of the type described in this invention can be used as a humidifier, for this application water is ejected into the air as an aerosol mist in order to increase the humidity. The humidifier is mains powered and does not need any power saving features, so an internal ledge is not required, nor is the maintenance of a particular droplet diameter critical. Therefore only one laser drilling step is undertaken and only the liquid entry section is reamed, giving a total of 2 steps. With just 2 steps a cost saving has been achieved with an acceptably small change in the performance of the nozzles in comparison to a membrane with 4 manufacturing steps

The laser process is now described, the laser is turned on and illuminates a spot on a membrane. If the power of the laser at the spot is sufficiently high it will cause ablation of the membrane. A percussion laser is preferentially used and over a number of pulses will progressively drill through the membrane. With each pulse not all of the laser energy causes ablation and recast melt is deposited in and around the illuminated spot. Recast melt is the re-solidification of molten material on the walls of the hole or on the surface of the membrane. A ripple of recast melt can develop with each successive pulse of the laser, the ripple is created by recast being deposited in a ring above the ablation spot. As the laser strikes the membrane a heat affected zone surrounding the illuminated area is created, in this area the microstructure of the metal is altered due to that heating. The thermal stresses inherent in laser drilling make microcracks likely to occur, these may be confined to the recast layer but can also pass into the parent metal itself. The microcracks are particularly liable to fracture during operation in a device causing contamination of the liquid being atomised. The recast melt causes decreased accuracy and repeatability of perforation diameter and nozzle geometry, it can cause partial or full blockages of the nozzles and increases the coefficient of friction of the nozzles. The decreased reliability of perforation diameter will feed through to decreased reliability in droplet diameter. The first laser pulse removes material at the illuminated spot on the surface of the membrane, the material removed matches that of the initial laser spot and the area below it. With further pulses the perforation becomes deeper and the area to be ablated no longer precisely in focus, has less power and becomes smaller. Consequently the perforation drilled is not cylindrical and will tend towards a number of different tapered shapes, a champagne flute, a trumpet flute, or wine glass shape are amongst those created. In metallic materials the taper can be pronounced with dramatic reductions in diameter from one side of the membrane to the other, this is caused by the hardness of the metal and is a particular problem. Current thermal drilling techniques in the sub 30 micron range have an aspect ratio at best of around 8 in stainless steel. If a 200 micron thick stainless steel membrane is to be laser drilled starting with a 25 micron hole it may taper to an exit hole of around 5 microns. In the subsequent reaming process the reamer may need to enlarge the exit hole and an adjacent section from 5 microns to 15 microns diameter. Removing stainless steel via abrasion is more time consuming and costly than via laser drilling it is therefore preferable to reduce the taper via laser drilling as much as possible and to use the reaming to hone and re-shape the nozzles. A reduction in the taper can be achieved by changing the focal distance of the laser and/or changing the power of the laser between successive laser pulses. For example a pulsed laser beam with a fixed power has a diameter of 10 microns at a chosen focal distance allowing 3 pulses to penetrate a membrane of 60 microns thickness. For the first pulse the laser is focused on the membrane surface nearest to the laser and a hole of depth 20 microns is drilled, then the membrane is raised 20 microns, now the laser is focused at a depth of 20 microns below the surface of the membrane, now the second pulse is sent and a further depth of 20 microns removed leaving the hole 40 microns deep. The membrane is now raised a further 20 microns and the third pulse sent, the laser penetrates the membrane. The exit hole diameter is 9 microns. As a comparison the same laser is focussed on the surface of the same membrane, as before the beam is 10 microns in diameter at the surface and 3 pulses are sent from the laser, however the height of the membrane is not adjusted after each pulse, now the exit hole has a diameter of 6 microns. This method can also be obtained if the laser is initially focused at the bottom surface of membrane and then the membrane is lowered. As an alternative the focal distance can remain fixed at either surface of the membrane however after each pulse the power of the beam is increased or decreased. The two methods can be combined so that both the focal distance and the power can be changed after each pulse. This technique is integrated into the laser apparatus so that it is automated and allows the process to occur quickly and efficiently. While relatively thick metallic materials are preferred for our membranes thinner metallic membranes or those made of less hard materials may allow the laser focus and power level to remain static.

Upon completion of laser drilling a next phase of micro reaming is undertaken. At its simplest a reaming tool is a cylindrical metal rod that has multiple diamond shards glued to its exterior, the reaming tool is inserted inside a hole that needs reshaping or smoothing and rotated, as diamond is a very hard material the shards in contact with the hole remove material via abrasion. In our invention the reamers are made especially for each individual step in the process and have micro sized diamonds bonded to their outer surface. An alternate technique is to create a reaming tool without bonding diamonds to the tool, however then the tool is lowered into the hole to be reshaped and an abrasive liquid containing micro sized diamond fragments is poured into the hole, as the tool is rotated the abrasive liquid removes material. A computer controlled mechanism adjusts the force, rotation speed, and depth of reaming. It also allows automation of the process for a plurality of perforations to be reamed without manual resetting. A specialist reaming service can be employed for example Microcut Switzerland.

The inventors have found that subsequently reaming the hole can remove much of the recast melt left behind by laser drilling. Recast melt is deposited during the laser drilling process in three major ways, firstly as burring whenever the laser first strikes the membrane, secondly as a ripple on the interior of the hole and thirdly as a layer of metal that is uneven. With each pulse of laser light recast melt can be left at the hole resembling a ring torus, for the first pulse this leaves a burr around the entry hole on the surface of the membrane. For each subsequent pulse as the hole becomes deeper a new ring torus may be deposited at the lowest depth, this leaves the completed hole with an undulating surface or ripple between the entry and exit surfaces. This recast melt can be understood as surface roughness of the hole interior. By convention every 2 dimensional surface roughness is denoted by a capitalised R followed by a lowercase letter denoting the exact parameter of roughness. The term Rp specifies the maximum peak height of a surface from its ideal form. If a hole created with a laser has a surface roughness Rp= 1 micron this signifies the recast has a maximum peak height of 1 micron, a reamer is then chosen to have a diameter that is 2 microns larger than the entry diameter of the laser drilled hole allowing for the removal of the recast. The same laser drilled hole when subsequently reamed can readily achieve a surface roughness of Rp=0.2 microns. The diameter of the reamer should be the largest diameter of the section being reamed plus at least twice the value of Rp to ensure substantial removal.

The regularity of the internal geometry of the nozzles directly affects the volume and repeatability of ejected droplets. Atomisers can be used as medical nebulisers and droplets that are either too large or small may not be ingested correctly into the lungs leading to a reduction in the efficacy of the medicine. For other atomisers the visual appeal of the aerosol plume is important and a consistent droplet diameter improves this appeal. Passage through the nozzles is greatly affected by imperfections such as partial blockages that will reduce the volume of a particular nozzle such that less liquid will be available for atomisation in that particular nozzle. In regularising the volume of each nozzle any section with a taper can have it removed via reaming leaving that section cylindrical. Reaming will produce nozzles with much tighter diameter tolerance than laser drilling alone, laser drilling can produce perforations with a particular entry diameter tolerance of 2-3 microns however subsequent reaming can reduce the tolerance on this diameter to 0.5 microns. Removing burrs from the membrane surfaces is advantageous because the recast melt has a capillary like structure which can cause unwanted fluid flow over the surface of the membrane near each nozzle resulting in uncontrolled droplet creation in aerosol devices. The burring can be removed at the earlier laser drilling stage by the use of a mask, in this circumstance the mask is placed on the surface so that the laser energy will pass through it before striking the membrane, burring will then land on the mask which can be disposed of upon completion of laser drilling. Alternatively a brush can be placed on the reamer above the micro diamond shards, as the reamer is lowered into the hole the brush will remove burring. The simplest method of removing burring is with a mask and this is the preferred method.

Ultrasonic atomisers can be utilised in portable devices, in order to make them easier to carry it is preferable to reduce the weight and the number of batteries they work with, consequently power saving is a goal of the present invention. A reduction in power consumption can be achieved by reducing the backwards flow of liquid inside the nozzles as the membrane vibrates backwards and forwards. This can be achieved by creating a membrane with nozzles that have three sections, a liquid entry section, middle section and liquid exit section and ensuring there is a portion of the nozzle between the middle and exit sections where the cross sectional area changes rapidly, previously referred to as a ledges. As the flow is strongly affected by the smallest middle section a ledge between the entry and middle sections does not materially affect flow. Ledges in the sub 5 micron width range can be created by honing the nozzles with a reamer. As an example consider a membrane that is 150 microns thick, a laser drill creates a hole in the membrane that tapers evenly so that it is 30 microns in diameter at the first surface, 20 microns halfway through and 10 microns at the second surface, now the membrane is turned over and the 10 micron hole enlarged by laser drilling to 40 microns but only to a depth of 45 microns. The membrane is turned over and a reamer with a diameter of 30 microns is lowered into the hole that is 30 microns in diameter but only to a depth of 75 microns so that material is removed. Now the membrane has a nozzle with 3 sections, a section that is 40 microns in diameter and 45 microns deep, a middle section that tapers from 16 microns to 20 microns in diameter and is 30 microns deep and another section that is cylindrical and has a diameter of 30 microns and is 75 microns deep. There is now a defined ledge of width 5 microns between the reamed section and the middle section. A further mechanism to reduce power consumption is inherent in the reaming process, nozzles with walls that have low surface friction will also have a low viscous drag thereby increasing the volume of flow for a given power input. It is therefore an aspect of this patent that narrow ledges can be created inside nozzles that are deep.

The geometry of the nozzles at any point through the membrane include but not exclusively a diameter at most of 40 microns because above this level dripping becomes a problem. At this time reamers have a minimum diameter of 15 microns and as they approach this diameter the risk of the reamer breaking increases. A single breakage can cause the membrane to become a failure because the reamer may become lodged inside the membrane and impossible to retrieve, to mitigate this risk the smallest diameter section is left unreamed. The rate of flow in a nozzle is strongly determined by this unreamed section. This can be understood by reference to Poiseuilles's equation for capillary flow in laminar nozzles.

$$T= [(\pi q^4)/8m] [(v_2-v_1)/w]$$

Where T= flow rate of liquid
q= radius of capillary/nozzle
m=viscosity of fluid
w= length of channel
And $(v_2-v_1)/w$= the average pressure gradient along the nozzle

The rate of flow is affected by the length of the channel (w) and by the fourth power of the radius (q^4) with shorter lengths associated with more flow. Therefore reducing the length of the smallest diameter section is an important feature for nozzle design. As the smallest diameter section is unreamed an advantage of reducing the length of this section is that a greater part of the nozzle is reamed thus removing more recast melt and regularising a greater length of the overall nozzle.

All of the nozzles are intended for use in a forward taper device, in a 2 section membrane the smallest diameter section is the exit section from which droplets emerge and reaming is carried out such that this section is shorter in length than that of the largest diameter section. In a 3 section nozzle the middle section has the smallest diameter, the entry section from which bulk liquid enters the membrane is the largest diameter section and the droplet exit section has a diameter that is neither the largest nor the smallest. The membrane is designed such that the middle section is shorter in length than both of the other two sections. The largest diameter section if it is to undergo reaming is reamed to the depth of the hole drilled in the previous laser step, this allows the reamer to remove a minimised amount of material.

Perforate membranes can contain several thousand nozzles or more. While each laser drilling step can be completed relatively quickly each reaming step takes longer. Reamers with a thickness in the vicinity of 20 microns diameter or less will fracture if the abrasion process is performed in a fashion that is too robust, this can be mitigated by removing material more slowly but this increases the machining time and cost. Consequently while all of the nozzles in a membrane will be laser drilled not all may be subsequently reamed. The extent of reaming will be determined by the final application, a medical nebuliser may require each nozzle to be reamed to remove recast melt, however an inexpensive air freshener may not have each nozzle reamed. For example a membrane has a total of one thousand nozzles, an inner portion of 500 nozzles are reamed but the remaining 500 are not reamed. In practise flexibility is required in the choice of the number of nozzles to be reamed.

Summary of Diagrams

Fig 1: Diagrams illustrating the laser drilling of a membrane to create perforations.
Fig 2 & 3: Diagrams illustrating the subsequent reaming of the perforations to create a nozzle in the membrane.
Fig 4a) Illustrates a top down view of a nozzle after laser drilling. Fig 4b) illustrates a top down view of a nozzle after reaming is completed. Fig 4c) shows a close up view of a number of nozzles in the membrane after reaming is completed.
Fig 5: Shows 2 alternate nozzle geometries created with this technique.
Fig 6: Illustrates an ultrasonic atomiser.
Fig 7 & 8: Shows a perforate membrane used in an ultrasonic atomiser from the front and also from the side.
Fig 9: Shows a close up of a perforate membrane in operation highlighting the nozzles.

Detailed Example of the Manufacturing Technique

The manufacturing technique to create a membrane with nozzles will now be described with reference to the diagrams. The diagrams are not held to scale in order to aid the description.

Fig 1a) shows a picture of a membrane [70], it is flat, 150 microns (um) thick and made of stainless steel. A laser beam [21] is shown prior to the beam striking the membrane for the first time, an arrow indicates the direction of the laser beam which is perpendicular to the front surface [72] of the membrane, the laser beam has a diameter of 18 microns at the point of contact, the laser is focused at the membrane surface so the maximum laser energy is at this surface. Fig 1b) Shows the hole after 4 pulses of laser energy have struck the membrane. A partial hole [22] has been created and recast melt [23] has been deposited on the surface of the interior of the hole. The recast melt is indicated by the thick and uneven markings on the surface of the hole. The hole diameter at the front surface [72] is 18 microns and it is 50 microns deep. Burring has not occurred, however it can appear as deposits of stainless steel in a ring around the hole on the front surface [72], a mask can be placed on the surface to be drilled prior to drilling, such that the burring is then captured on the mask which is subsequently removed and disposed of, this does not alter the performance of the drilling, the mask is optional and not shown. Fig 1c) shows the laser [21] just about to strike the membrane hole [22], the focus of the laser has been changed by raising the membrane in height by 50 microns, the new focal distance is indicated by the line [29] and is known by prior experimentation to be the lowest depth of the first hole. The laser will therefore offer the maximum power to the bottom of the hole. The diameter of the laser beam is unchanged. Fig 1d) shows the hole created after a further 4 pulses of laser energy, the hole is now 100 microns deep and a ripple has been formed, this is noted in the recast melt [23] as four curves, hereafter the ripples are not shown. Fig 1e) shows the laser just prior to striking the membrane once again, the focal distance of the laser [29] has been changed by raising the membrane by a further 50 microns, the maximum power density will now be incident on the bottom of the hole, the laser apparatus is otherwise unchanged. Fig 1f) shows the hole after a further 4 pulses of laser energy, the membrane has been penetrated so that the hole passes right through. The recast melt [23] covers the entire inner surface. The exit hole diameter at the surface [71] is approximately 14 microns. The focal length of the laser does not need to change as described in fig 1a) to 1f), the laser could remain focused at the surface [72] to drill through the membrane with successive pulses. For comparison Fig 1i) shows this circumstance, while the entry diameter is the same at 18 microns the exit diameter is 5 microns. Fig 1g) shows the membrane in fig 1f) turned over, so that now laser energy can be applied to the rear surface [71], alternatively the membrane could be drilled from below, this is not shown. The laser is re-aligned so that the subsequent laser beam is central to the hole [22]. The laser beam [21] is focussed at that surface and is shown just prior to striking the membrane. The beam diameter of the laser has now been changed to 28 microns at the focal length and three laser pulses are sent to the membrane. The nozzle shown in Fig 1h) has been created with a diameter of 28 microns at the surface [71] and a depth (a) that is 30 microns. Note that recast melt [23] has been deposited on the entirety of the inner surface of the hole [22], this by product of laser drilling is unwanted as noted in the aforementioned discussion. Note that at the interchange between the two laser drilling steps at the depth of 30 microns a substantial amount of recast is present and that the laser process alone is not accurate enough to create defined and substantially flat ledges. Note also that the hole is not symmetrical about an imaginary line [25] through the centre of the hole, indicating that the typical tolerance of the laser drilling process and recast melt deposited have left the hole relatively coarse and with lower quality than is desirable. The dimensions of this hole in the membrane are 28 microns at the rear surface, 18 microns at the front surface and 15 microns at a depth of 50 microns from the surface [71]. The recast melt layer is 1 micron thick at its maximum peak height.

Fig 2a) shows the membrane from fig 1h) prior to reaming, the hole to be reshaped is 28 microns in diameter. The reamer [30] is shown above the hole [22] and is 30 microns in diameter allowing for the removal of the recast melt layer. The reamer is centred to accurately match the hole previously drilled by laser. The reaming tool has micro diamonds [31] bonded to its surface. The reaming tool rotates at 1,000 revolutions per minute in the direction shown by the arrow [32]. Fig 2b) shows the reaming tool after it has been lowered normal to the surface into the hole, it is lowered to a depth of 30 microns below the rear surface [71] of the membrane. The depth is chosen to match the depth previously drilled by laser in fig 1h), it is left in place until the abrasion is complete and then removed. Fig 2c) shows the hole with a newly created section [73]. Notice that the recast melt has been removed from this newly created section of the hole as indicated by the flat sides to the section but that recast remains on the remainder of the hole. Notice also that the section [73] is now symmetrical about the imaginary line [25] forming a cylinder with the taper formerly present no longer apparent. The reamed section has a depth (a) of 30 microns and a diameter of 30 microns.

Fig 3a) shows the membrane in fig 2c) however it has been turned over so that the front surface [72] is on top. The reamer [30] has been changed and now has a diameter of 20 microns, it has been aligned to be central to the hole [22] and the number of revolutions at 1,000 per minute stays the same. Fig 3b) shows the reaming tool [30] after it has been lowered into the hole. The reamer is lowered to a depth (c) to leave the middle section that is to be left unreamed 20 microns in depth. The diameter of the reamer is chosen to remove the ripple and recast melt. The reamer removes material by abrasion until all of the unwanted material is removed and is then taken out. Fig 3c) shows the completed nozzle with 2 newly created sections [74] and [75]. Notice little or no recast melt remains on the inner surfaces of sections [73] and [75] of the nozzle as indicated by the flat surfaces. Little or no taper remains in any part of the nozzle and the sections [73] and [75] are cylindrical and concentric around the dotted line [25] with a high degree of nozzle quality. A new flat internal ledge [24] which is 2.5 microns across has been created between the section [74] and [75] with a defined edge. The section [73] has a diameter of 30 microns and a depth (a) of 30 microns. The section [74] is approximately 15 microns in diameter and has a depth (b) of 20 microns. The section [75] is 20 microns in diameter and has a depth (c) of 100 microns. Notice that the unreamed middle section is the shortest in length and smallest in diameter.

Fig 4a) shows a top down and close up view of the rear surface [71] of the membrane after laser drilling has taken place so that the single hole 1h) is viewed, only the first section to the depth of 30 microns is detailed. The entry hole of the laser at the rear surface is represented by the uneven and bounded line [27] and is 28 microns in diameter. The ripple and taper from a depth of 0 to 30 microns is represented by two uneven and bounded lines [28]. The start of the middle section at the depth of 30 microns is represented by the bounded line [26]. Variation in the laser drilling has left the hole unsymmetrical, it has a taper, recast melt and it is not cylindrical. Fig 4b) shows a top down view of the rear surface [71] of fig 3c). Both laser drilling and reaming of the hole has taken place to leave a completed nozzle allowing comparison with Fig 4a) and demonstrating the effect of reaming. Notice the bounded lines [26] and [27] have now become circular. This indicates that this section has become cylindrical with a new diameter of 30 microns, the taper, ripple and recast melt have been removed while nozzle quality has been optimised. The bounded lines [28] are no longer present indicating a ledge has been created between the perforations [26] and [27] that has a width of 2.5 microns. Fig 4c) shows a close up of the rear surface [71] of the perforate membrane that illustrates an array of nozzles. The array is formed from a plurality of nozzles [80] placed to form an equilateral triangle, an equilateral triangle pattern is chosen because it allows the nozzle diameter [81] to be increased close to half of the distance between nozzles [82] thus maximising the potential number of nozzles that can be packed into the array. In this example [81] is set at 30 microns and one side of the equilateral triangle [82] has a length of 150 microns.

Both the laser drilling and reaming are controlled electronically to automate the production process. There are a total of 1,000 nozzles arranged in the array that is central to the membrane. The laser drills all 1,000 perforations as noted in fig 1a) to 1f) consecutively followed by all 1,000 perforations as noted in fig 1g) to 1h) consecutively. The reaming is then carried out with all 1000 perforations reshaped consecutively as noted in fig 2, followed in the same fashion for the perforations drilled as noted in fig 3.

Further Examples of Nozzle Geometries

It is intended that this patent encompasses perforate membranes containing the nozzle geometries as also seen in Fig 5. The technique to create the nozzles in Fig 5 is noted below but focuses on the reaming as the other aspects of creating a perforate membrane are the same as in the example above.

Fig 5a) shows a nozzle geometry that is created via laser drilling from both sides of the membrane to leave the perforations as described for fig 1h) thereafter the reaming process is carried out only on section [75]. The nozzle is identical to that described in fig 3c) except section [73] is not reamed. Recast melt [23] is present on the surface of sections [74] and [75] and the tapering created in the earlier laser drilling step is still apparent. A ledge [24] is present that is 2.5 microns wide at the intersection between sections [74] and [75]. The section [73] is 28 microns wide and has a depth (a) of 30 microns, the section [74] is approximately 15 microns in diameter and has a depth (b) of 20 microns and the section [75] is 20 microns in diameter and has a depth (c) of 100 microns. Notice the middle section is the shortest in length. Fig 5b) shows a nozzle geometry that is laser drilled from the rear side [71] only so that laser drilling is complete as described for fig 1f). Thereafter the reaming is carried out only on section [73] with a reamer of 20 microns diameter to create a cylindrical section that has a depth (a) of 100 microns deep. Section [75] is not reamed and therefore retains its taper and recast melt, it has a depth (c) of 50 microns. Notice the nozzle is substantially symmetrical around the imaginary line [25]. Notice also that section [73] has had its recast melt removed and is longer in length than section [75].

Creation of an Ultrasonic Atomiser using the Invented Membranes

The perforate membranes created via the techniques noted in Fig 1 to Fig 5 above are to be used in an ultrasonic atomiser. This can include aerosol generators, humidifiers, inkjet devices and other apparatus. The atomiser converts liquid in contact with it into liquid droplets emergent from it. Liquid is understood to include pure liquids, mixtures of liquids, solutions, and suspensions of particles in liquids. All of the membranes are used in the forward taper configuration.

The Resulting Atomiser

The resulting atomiser has a number of advantages over prior art devices. There is no pressure bias needed during the operation of our atomiser and there is no dripping from the nozzles with its consequent uncontrolled atomisation. If desired an atomiser apparatus can have relatively large droplets up to 40 microns diameter or a majority of droplets having a diameter of over 30 microns while operating at frequencies below 150KHz, something not hitherto observed in forward taper devices. Relatively larger droplets allow a greater rate of spray for a given power level and the addition of an internal ledge helps prevent the backwards flow of liquid, this results in fewer batteries and a more portable device. The lower operational frequency allows for cheaper drive electronics with a consequent reduction in per unit manufacturing cost. The regularised nozzle geometry allows for a more consistent droplet diameter which improves the visual appeal of the aerosol mist. Recast melt can be removed such that it poses no risk of medicine contamination.

Detailed example of an Ultrasonic Atomiser utilising the created membrane

One example of how the membranes created in Fig 1 to Fig 5 can be used in an ultrasonic atomiser is now detailed. The present invention is not intended to be limited to the exact construction technique described below.

Fig 6 shows a droplet generating apparatus [60] comprising an ultrasonic atomiser [50] that is held in a container [61] by a soft silicone rubber (not shown), the atomiser is able to vibrate and is not clamped, the container has 3 solid sides and holds a liquid [62] that is in contact with the rear face of the ultrasonic atomiser, liquid is only able to exit the container through the atomiser. The drive electronics with integrated power supply [63] supply a sine wave of 100V peak to peak amplitude and frequency 100KHz through the power leads [64] to the atomiser. The atomiser is operated in the bending mode at a frequency just below its resonant frequency producing a vibration known to produce the highest rate of atomisation. There are a range of frequencies from which atomisation can take place, for the part described they are 90-110KHz. Liquid enters the atomiser and exits the front face of the atomiser as droplets [65]. No pressure bias is applied.

Fig 7 shows the ultrasonic atomiser from the front while Fig 8 shows the same part from the side. The ultrasonic atomiser [50] is comprised of a circular stainless steel ring [51], the stainless steel perforate membrane [70] is given two arrows that are used to illustrate that it is a single concentric disc of stainless steel however the central part has been machined by laser drilling and reaming and contains an array of nozzles [54] through which liquid is atomised. The membrane will be understood to comprise nozzles centred around the middle of the membrane. The membrane and the stainless steel ring are bonded to a piezoelectric ring [52] using an electrically conducting epoxy resin. The stainless steel ring and perforated membrane are not in physical contact. Power from the drive circuitry passes through the power leads (not shown) and enters the piezoelectric ring via the electrode [53] and via the stainless steel ring to a second electrode on the underside of the piezoelectric ring (not shown). The stainless steel ring acts as a mount allowing relatively unrestricted movement of the perforated membrane while being vibrated by the piezoelectric ring. The stainless steel ring has an outside diameter of 30mm and an inside diameter of 18mm. The piezoelectric ring is made from PZT type Navy VI and has an outside diameter of 23mm and an inside diameter of 15mm. The perforate membrane consists of a stainless steel disc with a diameter of 17mm with the mesh having a central area covering a 6mm diameter. Both the stainless steel ring and perforate membrane are 0.15mm thick.

Fig 9 shows a close up and cut away diagram of Fig 6 focusing on the array of the perforate membrane. For illustrative purposes the membrane contains three nozzles although it will be understood that in actuality it would contain many more. The chosen nozzle is that shown in Fig 3c) with the dimensions noted in the discussion of Fig 3. Fluid [62] enters the rear face [71] of the mesh via the nozzles [80]. The mesh is subjected to a bending mode vibration by the piezoelectric ring during operation and the nozzles empty in a cyclic fashion. The droplets [65] have a mean diameter of 35 microns and exit the nozzles from the front face [72] and are propelled away from the mesh forming an aerosol mist.

CLAIMS

1. A method of forming a perforate membrane for use in an ultrasonic atomiser by applying focused and pulsed laser energy to a membrane in a selected pattern in order to form a plurality of perforations with each perforation formed by changing the focal distance of the laser and/or its energy after each pulse or a number of pulses in order to reduce the taper of the perforations as they pass through the membrane from the front surface to the rear surface, then;

reaming the perforations into two distinct sections to produce nozzles with a reamed section that is smooth and cylindrical choosing the reamer diameter to be the diameter of the perforations at the rear surface plus at least twice the maximum peak height of the recast melt leaving one section unreamed that is shorter in length than the reamed section.

2. A method of forming a perforate membrane for use in an ultrasonic atomiser by applying focused and pulsed laser energy to a membrane in a selected pattern in order to form a plurality of perforations with each perforation formed by changing the focal distance of the laser and/or its energy after each pulse or a number of pulses in order to reduce the taper of the perforations as they pass through the membrane from the front surface to the rear surface then turning the membrane over and applying laser energy in a second laser drilling step to the perforations at the rear surface drilling down to a chosen depth less than that of the thickness of the membrane and enlarging the diameter of the perforations at the rear surface so they are greater than the diameter of the perforations at the front surface then;

reaming the perforations from the front surface to produce nozzles with three distinct sections choosing the reamer diameter to be the diameter of the perforations at the front surface plus at least twice the maximum peak height of the recast melt leaving the section smooth and cylindrical and reaming to a depth that leaves the middle section shorter in length than either of the other sections with a ledge at the intersection between the front surface sections and middle sections.

3. A method of forming a perforate membrane for use in an ultrasonic atomiser by applying focused and pulsed laser energy to a membrane in a selected pattern in order to form a plurality of perforations, then;

reaming the perforations into two distinct sections to produce nozzles with a reamed section that is smooth and cylindrical choosing the reamer diameter to be the diameter of the perforations at the rear surface plus at least twice the maximum peak height of the recast melt leaving one section unreamed that is shorter in length than the reamed section.

4. A method of forming a perforate membrane for use in an ultrasonic atomiser by applying focused and pulsed laser energy to a membrane in a selected pattern in order to form a plurality of perforations then turning the membrane over and applying laser energy in a second laser drilling step to the perforations at the rear surface drilling down to a chosen depth less than that of the thickness of the membrane and enlarging the diameter of the perforations at the rear surface so they are greater than the diameter of the perforations at the front surface then;

reaming the perforations from the front surface to produce nozzles with three distinct sections choosing the reamer diameter to be the diameter of the perforations at the front surface plus at least twice the maximum peak height of the recast melt leaving the section smooth and cylindrical and reaming to a depth that leaves the middle section shorter in length than either of the other sections with a ledge at the intersection between the front surface sections and middle sections.

5. A membrane for use in an ultrasonic atomiser according to claim 2 or 4 whereby a second reaming step also takes place on the rear surface section to the chosen depth in the second laser drilling step.

6. A membrane for use in an ultrasonic atomiser according to any of the preceding claims whereby not all of the laser drilled perforations are given a reaming step.

7. An ultrasonic atomiser using a membrane in the forward taper configuration formed according to any of the preceding claims.

8. An ultrasonic atomiser according to claim 7 whereby the aerosol from the atomiser in operation has a majority of droplets with a diameter over 30 microns.

Application No:	GB1404675.9	**Examiner:**	Mr Rhys J. Williams
Claims searched:	1 and in part claims 6-8	**Date of search:**	25 April 2014

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	US 2005/0006359 A1 (BLAKEY) See whole document.
A	-	WO 2012/168181 A1 (PARI PHARMA) See whole document
A	-	US 2011/0198321 A1 (WALTER) See whole document.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

B05B; B23K

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

International Classification:

Subclass	Subgroup	Valid From
B05B	0017/06	01/01/2006
B23K	0026/38	01/01/2014