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(71) Applicant: **OCE Holding B.V.**
5914 CA Venlo (NL)

(72) Inventor: **RASA, Mircea V.**
5914 CA Venlo (NL)

(74) Representative: **OCE IP Department**
St. Urbanusweg 43
5914 CA Venlo (NL)

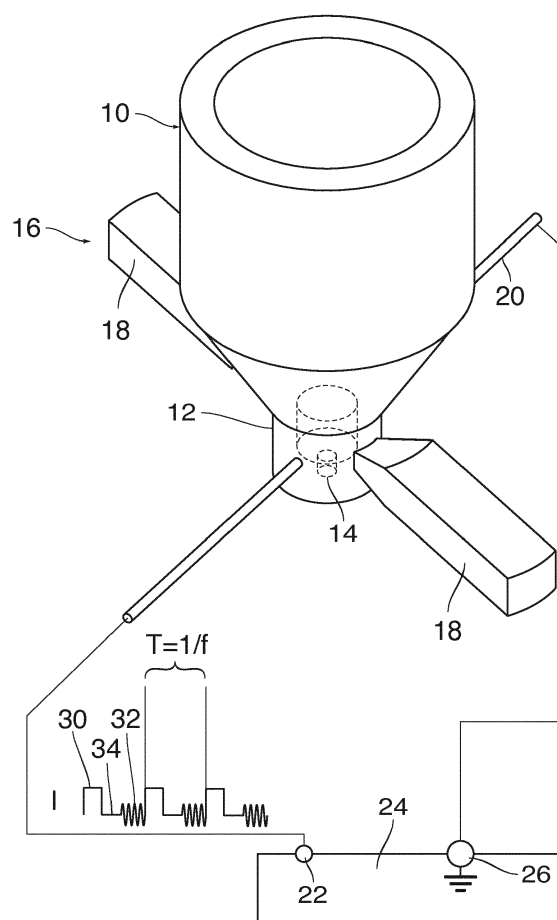
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(54) **METHOD OF CONTROLLING A TEMPERATURE IN A JETTING DEVICE**

(57) A method of controlling a temperature in a jetting device, wherein the jetting device comprises:

- a fluid chamber (12) connected to a nozzle (14) and containing an electrically conductive liquid (28) to be jetted-out through the nozzle;
 - a magnetic field generator (16) arranged to create a magnetic field in the fluid chamber (12);
 - a pair of electrodes (20) contacting the electrically conductive liquid in the fluid chamber; and
 - a controller (24) arranged to control a flow of an electric current (I) through the electrodes (20) and the electrically conductive liquid;
- wherein the electric current (I) is controlled to take the form of a sequence of alternating jetting pulses (30) and maintenance pulses (32), the jetting pulses (30) being configured to cause each a droplet of the liquid to be jetted out, and the maintenance pulses (32) being configured to agitate the liquid without jetting out a droplet, and wherein the jetting pulses (30) are generated at a variable jetting frequency (f), characterized in that a dependency of the average power dissipation of the current (I) on the jetting frequency (f) is suppressed by providing intervals (34) with reduced current amplitude between the jetting pulses (30) and the maintenance pulses (32).

Fig. 1



Description

[0001] The invention relates to a method of controlling a temperature in a jetting device, wherein the jetting device comprises:

- a fluid chamber connected to a nozzle and containing an electrically conductive liquid to be jetted-out through the nozzle;
- a magnetic field generator arranged to create a magnetic field in the fluid chamber;
- a pair of electrodes contacting the electrically conductive liquid in the fluid chamber; and
- a controller arranged to control a flow of an electric current through the electrodes and the electrically conductive liquid;

wherein the electric current is controlled to take the form of a sequence of alternating jetting pulses and maintenance pulses, the jetting pulses being configured to cause each a droplet of the liquid to be jetted out, and the maintenance pulses being configured to agitate the liquid without jetting out a droplet,

and wherein the jetting pulses are generated at a variable jetting frequency.

[0002] WO 2010/063576 A1 discloses a jetting device of this type which is used for jetting molten metal such as copper, silver, gold, and the like. The magnetic field generator creates a magnetic field that extends at right angles to a flow direction of the liquid when the liquid flows to the nozzle. The electrodes are arranged to create an electric current that is normal to both the magnetic field and the flow direction of the liquid. As a consequence, the electrically conductive liquid is subject to a Lorentz force that accelerates the liquid towards the nozzle, so that, when the electric current is applied in the form of a pulse sequence, droplets of the molten metal are jetted out from the nozzle.

[0003] When the jetting device is used for printing a two-dimensional image or a relief or a three-dimensional object from the molten metal, the jetting device will be scanned over a substrate on which the printed object is to be formed, and a jetting pulse will be generated whenever the nozzle reaches a position where a droplet of molten metal is to be deposited. Consequently, depending upon the details of the image or object to be printed, there may be time periods where droplets are to be jetted-out with a maximum frequency of, for example, 2000 Hz in order to form a solid layer of molten metal, and there may be other time periods where isolated droplets are to be formed only from time to time, so that the jetting frequency is relatively small and the jetting pulses are separated by relatively long intervals. The maintenance pulses, e.g. AC current pulses with a frequency in the radio frequency domain, may be applied in the intervals between the jetting pulses in order to prevent the nozzle from becoming clogged with solidifying metal.

[0004] Since the temperature of the jetting device and in particular the temperature of the conductive liquid has a significant effect on the droplet forming and jetting behavior, it is desired to keep the device at an approximately constant temperature in order to achieve a high jetting stability. However, changes in the jetting frequency may lead to significant temperature variations.

[0005] It is possible to control the temperature in a feedback or feed-forward loop, so as to keep the temperature constant even when the jetting frequency changes, as has been proposed for example in US 2014-076988 A1.

[0006] It is an object of the invention to provide a temperature control method that is more easy to implement.

[0007] In order to achieve this object, according to the invention, a dependency of the average power dissipation of the current on the jetting frequency is suppressed by providing intervals with reduced current amplitude between the jetting pulses and the maintenance pulses.

[0008] The invention takes advantage of the fact that the power dissipation of the electric current that flows through the conductive liquid constitutes a heat source that tends to increase the temperature of the liquid, especially in the fluid chamber in the vicinity of the nozzle where the temperature of the liquid has the largest effect on the jetting properties. On the other hand, effects such as thermal radiation, heat conductivity and convection cause a constant transport of thermal energy from the fluid chamber to the environment and therefore tend to reduce the temperature of the liquid. Consequently, it is possible to shift the equilibrium between power dissipation from the current and thermal losses and thereby to control the temperature of the liquid by inserting intervals or pauses with reduced current or no current at all between the jetting pulses and the maintenance pulses.

[0009] By appropriately setting the length of these low-current intervals, the effect of variations in the jetting frequency on the temperature of the liquid may be reduced significantly, so that other temperature control elements such as actively controlled heating or cooling elements may be dimensioned smaller or may be dispensed with completely.

[0010] Useful details and further developments of the invention are indicated in the dependent claims.

[0011] In one embodiment, the current amplitude in the low-current intervals is reduced to 10% or less of the current amplitude of the jetting pulses. More particularly, the current amplitude may be zero in the intervals.

[0012] The intervals may be inserted according to any suitable pattern before or behind each maintenance pulse and may even be nested within the maintenance pulse so that the latter is divided into two or more sub-pulses.

[0013] The total duration of the interval may be in a fixed proportion to the pulse width of the jetting pulse. Optionally, especially when the jetting pulse does not have a rectangular shape, the duration of the interval may be modified by

correction terms which are dependent upon the respective shape of the jetting pulse.

[0014] Embodiment examples will now be described in conjunction with the drawings, wherein:

Fig. 1 is a schematic perspective view of a jetting device according to an embodiment of the invention;

Fig. 2 is a sectional view of the jetting device; and

Figs. 3 - 5 are diagrams of different current waveforms.

[0015] As is shown in Fig. 1, a jetting device comprises a crucible 10 that has the shape of an inverted truncated cone and tapers towards a cylindrical fluid chamber 12 that opens out into a nozzle 14 at the bottom end.

[0016] The crucible 10 contains an electrically conductive liquid to be jetted, e.g. a molten metal. The walls of the crucible may contain heating elements (not shown) for keeping the metal in the molten state.

[0017] The entire device is preferably kept in an inert gas atmosphere, e.g. an argon atmosphere, in order to prevent the molten metal from being oxidized.

[0018] A magnetic field generator 16 is disposed at the outer periphery of the fluid chamber 12 and comprises a pair of magnetic field concentrators 18 arranged opposite to one another in a plane orthogonal to the common central axis of the fluid chamber 12 and the nozzle 14. The field concentrators 18 are formed by permanent magnets in this example. Optionally the may be formed of a magnetizable material and may be magnetized by means of electric solenoids.

[0019] A pair of electrodes 20 are arranged in the same plane as the field concentrators 18 and on a line that passes through the axis of the fluid chamber at right angles to the line connecting the field concentrators. The electrodes 20 pass through the wall of the fluid chamber 12 so as to be in electric contact with the molten metal in the fluid chamber and are electrically isolated from the wall of the fluid chamber. One electrode 20 is connected to an output terminal 22 of a controller 24, and the other electrode is electrically connected to a ground terminal 26 of the controller.

[0020] Thus, the controller 24 may control an electric current I flowing through the electrodes 20 and through the electrically conductive liquid in the fluid chamber 12.

[0021] In Fig. 2, it can be seen how the electrodes 20 contact the conductive liquid which is designated by the reference numeral 28. The field concentrators 20, which are not visible in Fig. 2, create a magnetic field that passes through the fluid chamber 12 in the direction normal to the plane of the drawing in Fig. 2. When the jetting device is operated for jetting-out droplets of the liquid 28 through the nozzle 14, a current pulse is passed through the electrodes 20, and the liquid in the fluid chamber 12 is subject to a Lorentz force that is directed downwardly and thus causes a droplet of the liquid 28, i.e. of the molten metal, to be jetted-out from the nozzle.

[0022] A waveform of the current I flowing through the electrodes 20 and the liquid in the fluid chamber 12 has been shown symbolically in Fig. 1 and in greater detail in Fig. 3 (current I as a function of time t). In this example, the waveform comprises a sequence of rectangular (DC) jetting pulses 30 alternating with maintenance pulses 32. The maintenance pulses 32 are AC pulses or RF (radio frequency) pulses, i.e. each maintenance pulse comprises a train of radio frequency oscillations with a frequency of more than 20 kHz, for example. The amplitude of these oscillations is smaller than the amplitude of the jetting pulses 30. While the jetting pulses 30 are strong enough to cause a droplet to be jetted out from the nozzle 14, the amplitude of the maintenance pulses 32 is not sufficient for creating a nozzle, but is just sufficient for agitating the liquid in the fluid chamber and in the nozzle and to dissipate heat energy into the liquid so as to prevent solidified metal and/or contaminants to settle in the nozzle orifice.

[0023] In the example shown in Fig. 3, each jetting pulse 30 and the subsequent maintenance pulse 32 are separated by an interval 34 in which the current is zero. Thus, a full period T of the current waveform is composed of one jetting pulse 30 having a duration or pulse width p , an interval 34 having a duration d , and a maintenance pulse having a duration $T-p-d$.

[0024] It will be observed that the period T is the inverse of the jetting frequency f with which the droplets are jetted out from the nozzle 14. In a practical "metal jet" application in which the jetting device is used for "printing" droplets of molten metal onto a substrate, the jetting frequency may vary within a broad range, e.g. between 2000 Hz and 10 Hz, during the print process, and the period T will vary accordingly. While the pulse width p of the jetting pulses 30 is constant, the length of the maintenance pulses 32 changes as a function of the period T and, consequently, as a function of the jetting frequency $f=1/T$. In general, the duration d of the intervals 34 may also be a function of the jetting frequency. In a useful embodiment, however, the duration d is independent of the jetting frequency, just as the pulse width p , so that the duration d is in a fixed proportion to the pulse width p .

[0025] In fact, it is possible to select the proportion between d and p such that the average amount of energy that is dissipated from the electric current into the liquid is practically independent of the jetting frequency f .

[0026] When I_j is the current amplitude of the jetting pulse and R is the electric resistance of the liquid 28, the Joule power that is dissipated during a jetting pulse 30 is $P_j = R I_j^2$. In order to calculate the average dissipated power over a jetting period T , P_j has to be integrated over the pulse width p , and the integral has to be divided by T , so that the power

contribution P_j of the jetting pulses will be

$$P_j = p R I_j^2 / T = p f R I_j^2 \quad (1)$$

[0027] Similarly, when I_{RF} is the current amplitude of the maintenance pulses 32, the dissipated power P_{RF} due to the AC current (sine wave) in the maintenance pulse 32 is

$$P_{RF} = (1/2) R I_{RF}^2 \quad (2)$$

[0028] However, given that the duration of an individual maintenance pulse 32 is only $T-p-d$, the average dissipated power P_M due to the maintenance pulse, averaged over the jetting period T , is given by

$$P_M = (1/2) [T-(p+d)] R I_{RF}^2 / T = (1/2) [1 - (p+d)f] R I_{RF}^2 \quad (3)$$

[0029] When the two contributions to the dissipated power (equations (1) and (3)) are added, the total average dissipated power P is given by:

$$\begin{aligned} P &= p f R I_j^2 + (1/2) [1-(p+d)f] R I_{RF}^2 \\ &= (1/2) R I_{RF}^2 + [p R I_j^2 - (1/2) (p+d) R I_{RF}^2] f \end{aligned} \quad (4)$$

[0030] Only the second of these two additive terms depends on the jetting frequency f , and the coefficient (in square brackets []) becomes zero when d is set to d_0 with:

$$d_0 = [(2I_j^2 - I_{RF}^2) / I_{RF}^2] p = A p \quad (5)$$

with

$$A = (2I_j^2 - I_{RF}^2) / I_{RF}^2 \quad (6)$$

[0031] Thus, when the current is controlled such that $d = d_0$, the time average of the dissipated joule power P is independent of the jetting frequency ($dP/df = 0$). This means that the amount of heat that is transferred to the liquid in the fluid chamber is independent of the jetting frequency. Since the mechanisms that tend to cool the liquid in the fluid chamber (heat radiation, heat conduction and convection) are also independent of the jetting frequency, the equilibrium temperature of the liquid is also independent of the jetting frequency. This greatly facilitates the control of the temperature of the liquid during a print process.

[0032] Even when d is not exactly equal to d_0 , dP/df will not become zero but will still be smaller than $[p R I_j^2 - (1/2) p R I_{RF}^2]$, which is the coefficient in equation (4) for the case $d = 0$ (i. e. with no intervals 34). When d is larger than d_0 , the heating power will decrease with the jetting frequency, and when d is smaller than d_0 , the heating power will increase with the jetting frequency.

[0033] Of course, the duration d_0 is only well defined on condition that A is positive, i.e. $2I_j^2 > I_{RF}^2$, a condition that can easily be met in practical applications. Further, d_0 must not be larger than $T-p$. Considering for example the maximum jetting frequency of 2 kHz and a typical pulse width $d = 60\mu s$ for the jetting pulse, this implies that I_j should not be larger than approximately $2 I_{RF}$. Together, both conditions can be satisfied if

$$0.7 I_{RF} < I_j < 2 I_{RF}.$$

[0034] This condition is met for example with $I_j = 60A$ and $I_{RF} = 57A$.

[0035] It is not compulsory that the interval 34 is located directly adjacent to the jetting pulse 30. Instead, the interval

34 may be provided at any location on the time axis between two successive jetting pulses. As is shown in Fig. 4, it is also possible that the interval 34 is divided into two parts positioned before and behind each maintenance pulse 32. It would even be possible to position the interval 34 or several parts thereof within the jetting pulse 32, so that the jetting pulse is divided into two or more parts.

[0036] In the examples discussed above, it has been assumed that the jetting pulses 30 have a rectangular shape. In a practical embodiment, it may take a certain rise time r for the current to rise from zero to the full current amplitude of the jetting pulse, and a corresponding time r may be needed for the current to drop from the full amplitude back to zero, so that the shape of the jetting pulse has more similarity with a trapezoid, as has been shown in Fig. 5. In that case, a calculation similar to the one discussed above in conjunction with Fig. 3 shows that the value d_0 of the duration d of the interval 34 for which the total dissipated power is approximately independent of the jetting frequency f takes the form:

$$d_0 = A p + B \quad (7)$$

with

$$B = [(4 I_j^2 - 6 I_{RF}^2) / 3 I_{RF}^2] r \quad (8)$$

[0037] This correction may also be generalized in a straightforward manner to the case that the trapezoidal jetting pulse is asymmetric, with a rise time r_1 for the leading flank different from the fall-off time r_2 for the trailing flank.

Claims

1. A method of controlling a temperature in a jetting device, wherein the jetting device comprises:

- a fluid chamber (12) connected to a nozzle (14) and containing an electrically conductive liquid (28) to be jetted-out through the nozzle;
- a magnetic field generator (16) arranged to create a magnetic field in the fluid chamber (12);
- a pair of electrodes (20) contacting the electrically conductive liquid in the fluid chamber; and
- a controller (24) arranged to control a flow of an electric current (I) through the electrodes (20) and the electrically conductive liquid;

wherein the electric current (I) is controlled to take the form of a sequence of alternating jetting pulses (30) and maintenance pulses (32), the jetting pulses (30) being configured to cause each a droplet of the liquid to be jetted out, and the maintenance pulses (32) being configured to agitate the liquid without jetting out a droplet, and wherein the jetting pulses (30) are generated at a variable jetting frequency (f),
characterized in that a dependency of the average power dissipation (P) of the current (I) on the jetting frequency (f) is suppressed by providing intervals (34) with reduced current amplitude between the jetting pulses (30) and the maintenance pulses (32).

2. The method according to claim 1, wherein the jetting frequency (f) varies between 2000 Hz and 10 Hz.

3. The method according to claim 1 or 2, wherein the maintenance pulses (32) are formed by AC current pulses with an AC frequency which is higher than the jetting frequency (f) and is preferably higher than 20 kHz.

4. The method according to any of the preceding claims, wherein the jetting pulses (30) have a pulse width (d) between 30 and 500 microseconds.

5. The method according to any of the preceding claims, wherein the current amplitude in the intervals (34) is less than 10% of the current amplitude in the jetting pulses (30) and is preferably zero.

6. The method according to any of the preceding claims, wherein the pulse width (d) of the jetting pulses (30) is independent of the jetting frequency (f).

7. The method according to claim 6, wherein a total duration d_0 of the interval or intervals (34) between two successive jetting pulses (30) is given by

$$d_0 = A * p,$$

wherein p is the pulse width of the jetting pulses (30) and A is a constant that is selected in accordance with the current amplitude I_j of the jetting pulses and the current amplitude I_{RF} of the maintenance pulses (32) such that

$$|dP/df| < (I_j^2 - 0.5 I_{RF}^2) p R$$

wherein R is the electrical resistance of the liquid.

8. The method according to claim 7, wherein

$$A = (2 I_j^2 - I_{RF}^2) / I_{RF}^2.$$

9. The method according to claim 7 or 8, wherein the jetting pulses (30) have a non-rectangular shape and the total duration d_0 of the interval or intervals (34) between two successive jetting pulses (30) is given by

$$d_0 = A * p + B$$

wherein B is a correction term dependent upon the shape of the jetting pulses (30) and selected to minimize $|dP/df|$.

10. A jetting device comprising:

- a fluid chamber (12) connected to a nozzle (14) and containing an electrically conductive liquid (28) to be jetted-out through the nozzle;
- a magnetic field generator (16) arranged to create a magnetic field in the fluid chamber (12);
- a pair of electrodes (20) contacting the electrically conductive liquid in the fluid chamber; and
- a controller (24) arranged to control a flow of an electric current (I) through the electrodes (20) and the electrically conductive liquid such that the electric current (I) takes the form of a sequence of alternating jetting pulses (30) and maintenance pulses (32), the jetting pulses (30) being configured to cause each a droplet of the liquid to be jetted out, and the maintenance pulses (32) being configured to agitate the liquid without jetting out a droplet, and the jetting pulses (30) being generated at a variable jetting frequency (f),

characterized in that the controller (24) is configured to perform a method according to any of the claims 1 to 9.

11. A software product comprising program code on a machine readable medium, the program code being configured to cause, when loaded into a controller (24) of a jetting device according to the preamble of claim 10, the controller to perform the method according to any of the claims 1 to 9.

Fig. 1

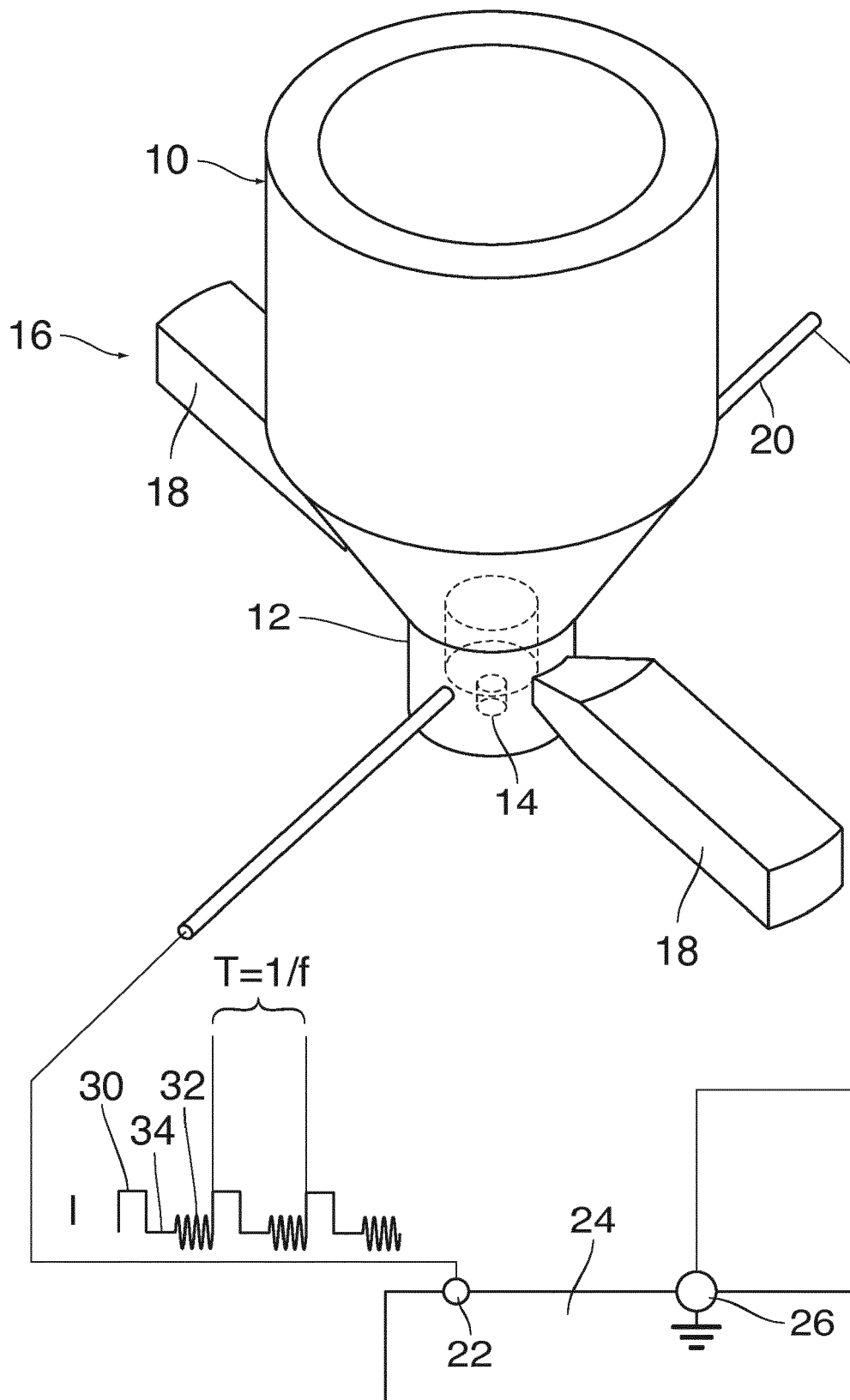


Fig. 2

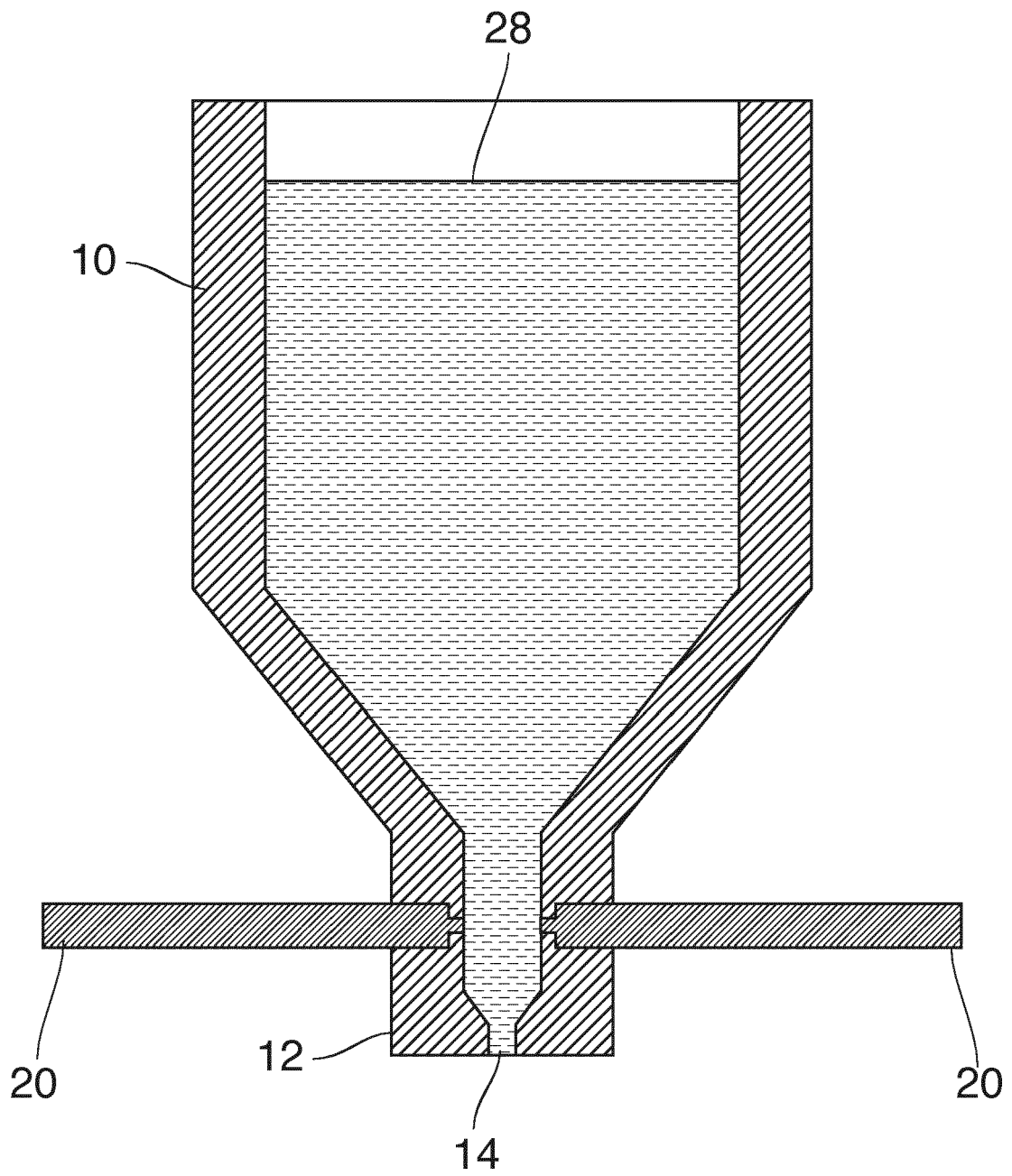


Fig. 3

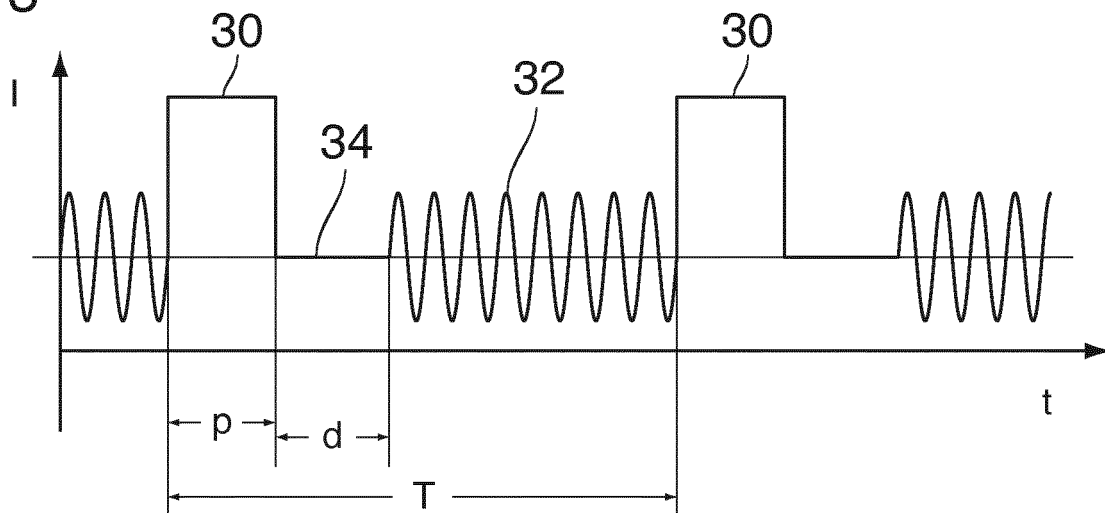


Fig. 4

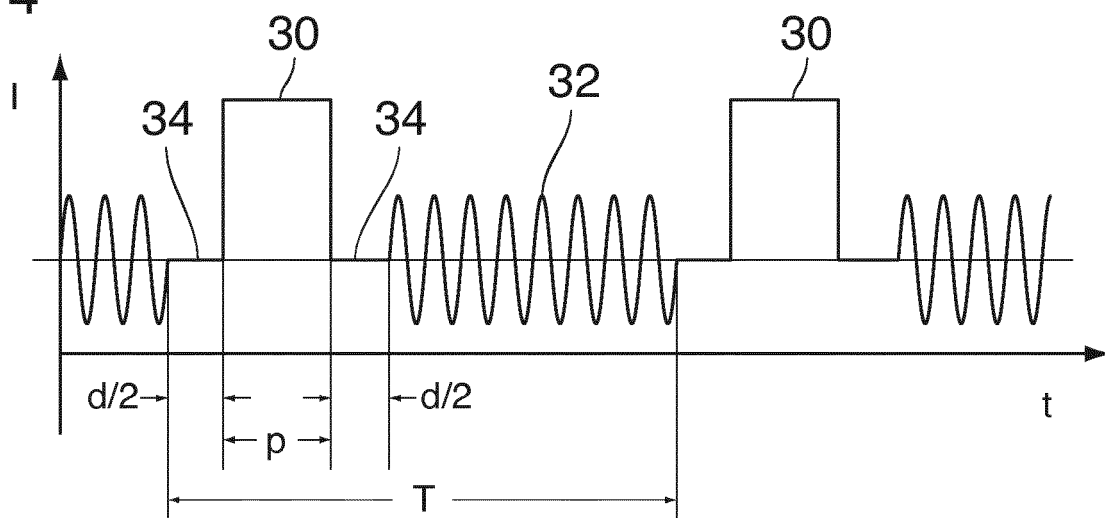
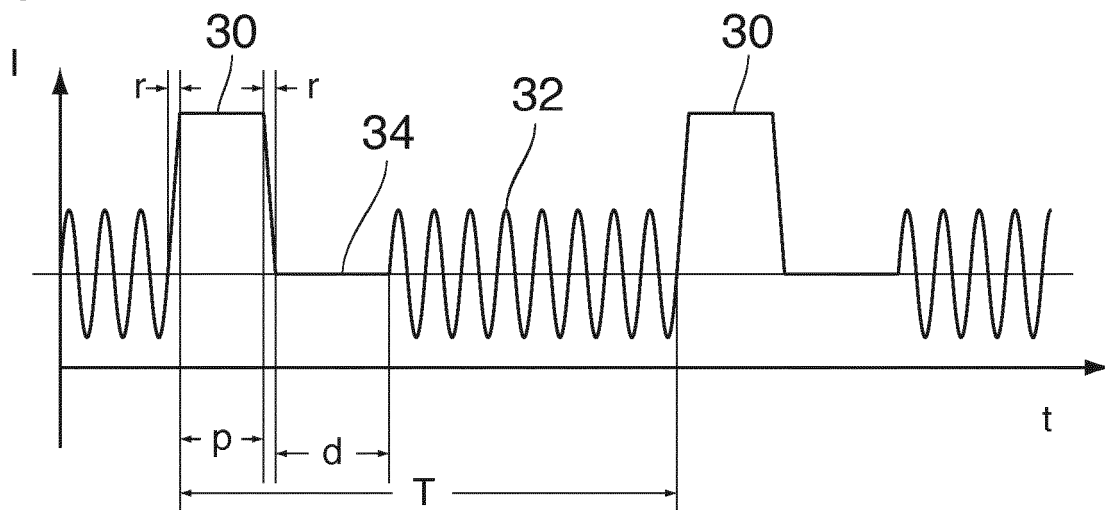


Fig. 5





EUROPEAN SEARCH REPORT

Application Number
EP 17 15 1664

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The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 13 June 2017	Examiner Didenot, Benjamin
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