TRIPLE-SHELL PIPE FOR TRANSPORTING CRYOGENIC LIQUID

Technical field

[0001] The invention relates to the field of liquefied gas transportation infrastructure, and more particularly to pipelines, or conduits, used to transport cryogenic liquids over long distances. The triple-walled conduits according to the invention are particularly well-suited for the transportation of liquefied hydrogen or helium.

Similar conduits are known from patent US4014369 A.

Prior art

[0002] Cryogenic liquids have numerous applications, for example:

- for nitrogen, in cooling, cryopreservation, dimensional contraction of objects before insertion into a tight housing (in the automotive industry), testing or inerting of products in the electronics industry,
- for oxygen, in rocket propulsion, medical oxygen, and the steel industry for steel production,
- for argon, as a thermal insulator, in light bulbs or welding baths,
- for helium, in the space industry and scientific research (e.g., for superconductors),
- for Liquefied Natural Gas (LNG), as a more sustainable alternative to conventional hydrocarbons.
- for liquefied hydrogen, as a carrier and means for energy storage which has the advantage of not generating CO_2 when burned.

[0003] Faced with these increasing applications, trade in cryogenic liquids has increased significantly, creating a substantial need for longer, safer, more cost-effective and more efficient (in terms of yield and ease and speed of assembly) industrial or scientific cryogenic facilities and cryogenic fluid transfer lines for above-ground, underground or underwater installations.

[0004] In the field of thermally insulated conduits for transporting cryogenic fluids, insulated transfer lines have been used for several years. The most robust of these lines consist, for example, of double-walled conduits comprising two concentric tubes:

- the inner tube is the conduit in which the cryogenic fluid circulates; this inner tube is inserted into an outer tube,
- the outer tube, into which the inner tube is inserted, has a diameter such that an annular space is created between the two tubes.

[0005] In these double-walled conduits, the annular space is used to install a thermal insulation, such as multilayer insulation coupled with a high vacuum (absolute pressure less than 10^{-4} mbar) associated with spacers to prevent the multilayer insulation from

being crushed under the weight of the inner tube and the conveyed fluid, or a microporous insulation coupled with a reduced pressure (absolute pressure less than 10 mbar at ambient temperature).

[0006] This double-walled system with thermal insulation in the annular space requires the use of materials compatible with cryogenic temperatures for the inner tube. To allow for the installation of straight and/or buried pipelines (without longitudinal flexibility elements such as bellows or expansion loops), the use of an alloy with a low coefficient of thermal expansion, such as Invar®, is particularly advantageous. Indeed, the thermal stresses occurring in the inner tube of the double-walled conduit during cryogenic heating are mechanically critical. In the case of a stainless steel inner tube, this type of conduit therefore requires special, regularly spaced junctions (every few tens of meters) between the inner and outer tubes, as well as a flexibility element to allow for relative movement between the inner tube at cryogenic temperature and the outer tube at ambient temperature. These junctions, which are necessary to prevent conduit rupture, constitute areas of lower thermal insulation, which impairs the overall thermal performance of the conduit.

[0007] To address certain risks of failure of inner or outer pipes, conduits insulated with a third layer have been proposed.

[0008] Triple-walled conduits offer the advantage of providing a double barrier in case of leakage in the tube transporting the fluid or rupture of the outer tube. These constructions also incorporate connecting parts that connect and maintain the various tubes within one another, the function of which is to control thermomechanical stresses and movement of the various tubes, but this also generates thermal bridges along the conduit and increased heat loss.

[0009] Thus, a triple-walled LNG conduit was proposed by the applicant (FR 2862741). It consists of an inner tube made of a low thermal expansion coefficient material such as Invar®, an intermediate tube made of carbon steel or stainless steel, and an outer tube made of carbon steel. Thermal insulation is placed in the inner annular space; additional insulation can be placed in the outer annular space to reduce the impact of thermal bridges at the junction parts between the inner tubes.

[0010] Document US20150219243 also details a triple conduit for long-distance LNG transport using the same arrangement.

[0011] A key characteristic of deep cryogenics is the increased need for thermal insulation, as cooling efficiency decreases with temperature, for example, 10 W of electricity is required to provide 1 W of cooling at 77 K, but 40 W at 20 K. The economic impact of the same heat transfer coefficient (expressed in $W/(m^2.K)$ is thus multiplied by 5 between the two temperatures (x4 for efficiency, x1.25 for the temperature difference).

Another characteristic is the amplification of mechanical stresses related to expansion and contraction phenomena.

[0012] A known method for improving the performance of thermal insulation is to reduce the gas pressure within the annular space. However, maintaining a low pressure is countered by the fact that hydrogen is a highly diffusive gas, and this pressure can tend to increase over time through diffusion across the inner conduit. Furthermore, leakage of the cryogenic liquid into the inner annular space, in addition to reducing efficiency, risks damaging the insulation, thus reducing thermal insulation performance and ultimately weakening the conduit.

[0013] A triple-pipe conduit for LNG transport is also known from document FR2865262. This conduit also has nanoporous insulation in the inner annular space and spacers to protect it from crushing between the inner and intermediate tubes. Furthermore, it uses concrete in the outer annular space for ballast. Therefore, it does not solve the aforementioned problem.

[0014] The applicant has developed a new triple-walled conduit that addresses these problems and is particularly well-suited for transporting cryogenic liquids, especially for deep cryogenic applications. This conduit can be used in underground, underwater, or aerial environments. The choice of materials used for its various components and their specific arrangement significantly reduce thermomechanical stresses within the conduit, allowing to create conduit sections on the order of a kilometer, free of any connecting parts. In the conduit according to the invention, the presence of connecting parts to mitigate thermomechanical stresses are only necessary at the conduit bends. Thus, the conduit according to the invention offers significantly improved efficiency and is particularly easy and quick to assemble. The conduit according to the invention also offers significantly improved safety and reliability. On the one hand, in the event of a leak of the cryogenic liquid through the inner tube, the thermal performance of the conduit is maintained: by ensuring the same temperature conditions outside the conduit, a leak in the tube carrying the cryogenic liquid has no impact on the outside of the conduit. On the other hand, the unique arrangement of the conduit according to the invention allows to connect it to a monitoring device for detecting leaks in the inner tube or permeation through the inner tube. The simplified structure of the conduit sections allows, if necessary, for easy replacement of the defective portion.

[0015] The conduit as developed by the applicant therefore allows to address the technical problems posed by prior art pipelines and by the growth of the market for the transport of cryogenic liquids.

Summary of the invention

[0016] The applicant has developed a new triple-walled conduit that is quick and easy to assemble. This conduit, particularly suited to the transport of cryogenic liquids, offers exceptionally high efficiency and improved safety.

[0017] Thus, an object of the invention is a conduit adapted for transporting a cryogenic liquid, thermally insulated, characterized in that it comprises

- three tubes arranged one inside the other:
  - an inner tube made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an intermediate tube made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an outer tube made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

    said three tubes arranged one inside the other defining an inner annular space comprised between said inner tube and said intermediate tube and an outer annular space comprised between said intermediate tube and said outer tube, the outer annular space comprising a microporous silica-based thermal insulation, the inner annular space not comprising any thermal insulation material
- connecting parts connecting said three tubes arranged one inside the other in pairs, located in the outer and inner annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner and outer annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27 wt% manganese,

in the case of connecting parts connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

[0018] This particular configuration allows in particular to limit the use of flexibility and expansion absorption elements between the inner and intermediate tubes at cryogenic temperature and the outer tube at ambient temperature, such as bellows or expansion loops.

[0019] The applicant has developed modular elements particularly adapted to constitute the conduit according to the invention, which further allow for quick and easy assembly of the conduit on site.

[0020] Thus, one of these modular elements, which is another object of the invention, is a unit of conduit adapted for transporting a cryogenic liquid characterized in that it comprises:

- three tubes arranged one inside the other:
  - an inner tube made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an intermediate tube made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an outer tube made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,
- said three tubes arranged one inside the other defining an inner annular space comprised between said inner tube and said intermediate tube and an outer annular space comprised between said intermediate tube and said outer tube,
- the outer annular space comprising a microporous silica-based thermal insulator, the inner annular space not comprising any thermal insulating material,
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27% by weight of manganese,
- in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

[0021] Another of these modular elements, which is also the subject of the invention, is a conduit fitting as described above, the fitting being characterized in that it comprises:

- three tubes arranged one inside the other:
  - an inner tube made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an intermediate tube made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$,
  - an outer tube made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

said three tubes arranged one inside the other defining an inner annular space comprised between said inner tube and said intermediate tube and an outer annular space comprised between said intermediate tube and said outer tube,
the outer annular space comprising a microporous silica-based thermal insulation,

- connecting parts connecting said three tubes arranged one inside the other in pairs, located in the outer and inner annular spaces, provided with at least one orifice so as to allow the circulation of gas in the annular spaces, said parts being made of an alloy with a coefficient of expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising 22 to 27% by weight of manganese),

in the case of connecting parts connecting tubes made of materials with different thermal coefficients, tubular transition parts are positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned,

- at the connecting part connecting said outer tube and said intermediate tube, an outer additional layer of microporous thermal insulation based on silica, surrounded by an outer connecting tube made of carbon steel, stainless steel, or austenitic alloy comprising 22 to 27 % by weight of manganese, said outer connecting tube being welded at its ends to the outer tube of the fitting.

[0022] Another of these modular elements, which is also the subject of the invention, is another conduit fitting as described above, the fitting being characterized in that it comprises:

- three tubes arranged one inside the other:
  - an inner tube made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$,
  - an intermediate tube made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$,
  - an outer tube made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

said three tubes arranged one inside the other defining an inner annular space comprised between said inner tube and said intermediate tube and an outer annular space comprised between said intermediate tube and said outer tube,
the outer annular space comprising a microporous silica-based thermal insulation,

- connecting parts connecting said three tubes arranged one inside the other in pairs, located in the outer and inner annular spaces, provided with at least one

orifice so as to allow the circulation of gas in the annular spaces, said parts being made of an alloy with a coefficient of expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising 22 to 27% by weight of manganese),

in the case of connecting parts connecting tubes made of materials with different thermal coefficients, tubular transition parts are positioned between the connecting parts and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

- at the connecting part connecting said outer tube and said intermediate tube, a thermal insulation layer opposite said connecting part is located in the inner annular space.

[0023] This type of fitting has the advantage of allowing the outer surface of the conduit to be maintained at a constant diameter, without any extra thickness even at the fittings.

[0024] Another modular element, which is also the subject of the invention, is an end-piece unit for a conduit according to the invention, the end-piece unit being characterized in that it comprises:

- a first part for closing the outer annular space welded on one side to an outer tube and on the other side to an intermediate tube, said part comprising an end of the intermediate tube adapted to constitute an extension to the intermediate tube of the conduit, and an end of the outer tube adapted to constitute an extension to the outer tube of the conduit,
- a second part for closing the inner annular space welded on one side to one end of the extension of the intermediate tube of the part for closing the outer annular space and on the other side to the inner tube, said inner tube comprising an end adapted to constitute an extension to the inner tube of the conduit,
- in the outer annular space (7), a layer of microporous silica-based thermal insulation,
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27% by weight of manganese,
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in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

[0025] This end-piece unit allows, at each end of the conduit, the inner and outer annular spaces to be closed.

[0026] Another modular element, which is also the subject of the invention, is an elbow conduit unit for a conduit as described above, the elbow conduit unit comprising:

- three tubes arranged one inside the other:
  - an inner tube made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$,
  - an intermediate tube made of a material with a coefficient of thermal expansion of less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$,
  - an outer tube made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

    said three tubes arranged one inside the other defining an inner annular space comprised between said inner tube and said intermediate tube and an outer annular space comprised between said intermediate tube and said outer tube,
  - the outer annular space comprising a microporous silica-based thermal insulation,
- said tubes arranged one inside the other having a curvature at an angle comprised between 30° and 90°
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27% by weight of manganese,

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

[0027] This elbow conduit unit allows for changes of direction to be introduced in the triple-walled conduit, depending, for example, on the terrain on or in which it is installed.

[0028] Depending on other optional characteristics, each of these different objects may optionally and independently include one or more of the following characteristics, alone or in combination:

- the material with a coefficient of thermal expansion less than or equal to $2.10^{-6}m.m^{-1}.K^{-1}$ constituting the inner tube and/or the intermediate tube is an iron-nickel alloy comprising 34.0% to 38.0% nickel, preferably 35.0% to 37.0% nickel, or even 35.5% to 36.5% nickel,
- the connecting or closing parts are made of an iron-nickel alloy comprising 34.0% to 38.0% nickel, preferably 35.0% to 37.0% nickel, or even 35.5% to 36.5% nickel,
- the inner tube and/or the intermediate tube have a thickness of at least 3 mm.
- the microporous thermal insulation has a density comprised between 40 $kg.m^{-3}$ and 250 $kg.m^{-3}$, between 70 $kg.m^{-3}$ and 190 $kg.m^{-3}$, preferably between 100 $kg.m^{-3}$ and 160 $kg.m^{-3}$, and/or
- the microporous silica-based thermal insulation comprises at least 50% silica, at least 60% silica, preferably at least 70% silica.

[0029] Depending on other optional features, the conduit according to the invention may optionally and independently include one or more of the following features, alone or in combination:

- the conduit comprises a segment of at least 10 m, at least 50 m, 100 m, 1 km, 5 km, 10 km or even at least 15 km in which the outer and inner annular spaces do not contain a fitting, in particular no fitting as described above.
- the conduit comprises an elbow conduit unit as described above and one of the fittings described above placed upstream and downstream of said elbow conduit unit.
- a gas is circulated in the inner annular space, said gas having, at the circulation pressure in the inner annular space, a liquefaction temperature lower than that of the cryogenic liquid transported in the conduit,
- one end of which is coupled to at least one means for analyzing the gas circulating in the inner annular space, or
- the pressure in the outer annular space (7), at ambient temperature, before the conduit is cooled, is less than or equal to 10 mbar.

Brief description of the figures

[0030] Other advantages and features of the invention will become apparent from the following description given by way of illustrative and non-limiting example, with reference to the appended Figures.

[0031] [Fig. 1] Figure 1 shows a section of a conduit unit 1 according to an embodiment of the present invention.

[0032] [Fig. 2] Figure 2 represents an end-piece unit 30 for conduit according to an embodiment of the present invention.

[0033] [Fig. 3] Figure 3 shows a fitting 20 for connecting conduit units 1 according to one embodiment of the present invention. The white space between the two connecting parts 9 is purely conventional to indicate that these two parts are separate; these two parts, as well as all the elements of the fitting 20, are of course welded together.

[0034] [Fig. 4] Figure 4 shows a fitting 21 for connecting units 1 of a conduit according to another embodiment of the present invention, known as a bayonet connection. The white space between the two connecting parts 9 is purely conventional to indicate that these two parts are separate; these two parts, as well as all the elements of the fitting 21, are of course welded together.

[0035] [Fig. 5] Figure 5 shows a cross-sectional view of a unit 1 of a conduit according to one embodiment of the present invention.

[0036] The relative scales of the different objects or elements are not respected to allow for proper visualization. The figures presented here are purely illustrative.

Description of embodiments

[0037] The inventive principle of the present invention is based on the integrated configuration of three tubes arranged one inside the other, combined with microporous thermal insulation in the outer annular space. This unique technical concept provides optimal insulation and a significant reduction in thermomechanical stresses over long distances. All proposed assembly variants, such as fittings, elbow conduit units and end-pieces, are specific adaptations of the basic inventive principle, which is based on a structure of three tubes arranged with microporous thermal insulation in the outer annular space. These adaptations allow for meeting assembly, flexibility, and integration requirements in specific installation configurations, while maintaining the overall technical effect of optimal insulation and reduced thermomechanical stresses.

[0038] The term “**conduit**” in the context of the present invention refers to an assembly for conveying one or more fluids or liquefied products from point A to point B. In a particular embodiment, the conduit according to the invention enables the onshore, buried or aerial, or offshore transport of one or more fluids or liquefied products from a fixed tank to a mobile tank in an export terminal, or from a mobile tank to a fixed tank in an import terminal. An example of a mobile tank could be a ship transporting said fluids or liquefied products over intercontinental distances. As discussed below, the conduits according to the invention are particularly well-suited for the transport of cryogenic liquids, such as liquid nitrogen, liquid oxygen, liquid argon, helium, liquefied natural gas (LNG), or

liquid hydrogen. The terms “conduit” and “pipeline” are interchangeable and may be used interchangeably.

[0039] The term “**tube”** as used in the present invention refers to a pipe or conduit for conveying a fluid or a mixture of fluids, and/or which may also comprise within its lumen another tube and/or another material. The conduit according to the present invention thus consists of several tubes arranged one inside the other.

[0040] The name “**annular”** or the terms “**annular space”** are used interchangeably. For the purposes of the present invention, they refer to the space formed between two tubes arranged one inside the other, said space being able to receive a flow of fluid and/or be filled with a material.

[0041] The term “**cryogenic fluid”** according to the present invention refers to cryogenic liquids such as liquid nitrogen, liquid oxygen, liquid argon, liquid helium, liquefied natural gas (LNG), or liquid hydrogen. In a preferred embodiment, the cryogenic liquids have a temperature lower than that of liquid nitrogen (-196°C/77 K, temperatures called deep cryogenic temperatures). In another preferred embodiment, the cryogenic fluid is liquid hydrogen or liquid helium. In a still more preferred embodiment, the cryogenic fluid is liquid hydrogen (liquid at 20 K). The terms cryogenic fluids and cryogenic liquids are used interchangeably herein.

[0042] The term “**coefficient of thermal expansion”** is well-known in the prior art and represents a measure of the reversible change in volume or length of a material with temperature. As mentioned above, contact with cryogenic fluids, which have particularly low temperatures, can generate phenomena of material contraction or expansion that create mechanical stresses on the constituent elements.

[0043] Unless otherwise specified, the intervals mentioned are understood to be inclusive. Thus, for example, a quantity described as being comprised between 5 and 10 or ranging from 5 to 10 may have a value of 5 or 10. For example, unless otherwise specified, a quantity described as being less than or greater than 10 may have a value of 10.

A first object of the invention is therefore the conduit as developed by the applicant which presents a particularly improved thermal efficiency and safety.

<u>Thermally insulated conduit adapted for transporting cryogenic fluid</u>

[0044] A conduit according to the invention is insulated and thermally adapted for transporting a fluid or mixture of fluids, preferably cryogenic fluids, is as mentioned above; certain embodiments are described in more detail below.

[0045] A conduit according to the present invention is in a triple-tube configuration or pipe-in-pipe-in-pipe (PIPIP). Thus, a conduit according to the present invention comprises three tubes 2, 3, 4 arranged one inside the other as illustrated in Figure 1 and Figure 5.

[0046] A conduit according to the present invention thus comprises a first tube, called the inner tube 2, defining a lumen (or inner space) 5 intended for the circulation of a cryogenic fluid.

[0047] The inner tube 2 is adapted for transporting one or more fluids, preferably cryogenic fluids. Thus, the inner tube 2 is adapted for transporting a cryogenic fluid or a mixture of cryogenic fluids at a temperature less than or equal to -160°C, preferably less than or equal to -190°C. Particularly preferably, the inner tube 2 is adapted for transporting a cryogenic fluid or a mixture of cryogenic fluids at a temperature less than or equal to -250°C.

[0048] The inner tube 2 is thus adapted for transporting cryogenic fluids such as liquefied natural gas (LNG), liquid nitrogen, liquid oxygen, argon, liquid hydrogen or liquid helium, preferably liquid hydrogen or liquid helium.

[0049] The inner tube 2 is made of a material with a low coefficient of thermal expansion, preferably a coefficient of thermal expansion less than or equal to 2.10^{-6} $mm^2.K^{-1}$. When the inner tube 2 is in operation within the conduit, that is to say, during the circulation of a cryogenic fluid in the inner space 5 (or lumen) of the inner tube 2, using a material with such a coefficient of thermal expansion prevents the higher mechanical stresses generated during contraction phenomena from exceeding the elastic limit of the material without the need to add longitudinal flexibility elements such as bellows or expansion loops, as is the case with other conduits of the prior art. Thus, this prevents ruptures of the inner tube 2 of the conduit and extends its service life.

[0050] Thus, the material constituting the inner tube 2 can be an iron-nickel alloy comprising at least 34.0% nickel, preferably at least 35.0% nickel, and even more preferably at least 36.0% nickel. In a further preferred embodiment, the material constituting the inner tube 2 can be an iron-nickel alloy comprising from 34.0% to 38.0% nickel, preferably from 35.0% to 37.0% nickel, or even from 35.5% to 36.5% nickel. In a particularly preferred embodiment, said iron-nickel alloy comprises 36.0% nickel. In yet another particularly preferred embodiment, said iron-nickel alloy is an Invar®. Invars have coefficients of expansion particularly adapted to the transport of cryogenic fluids. Furthermore, Invar® type alloys have certain mechanical properties, such as yield strength and tensile strength, that are higher at cryogenic temperatures compared to those measured at room temperature. Therefore, mechanical sizing of the tube based on the room-temperature mechanical properties of Invar® is conservative for a cryogenic line. To optimize sizing by reducing the Invar® tube thickness for a cryogenic application, it may be advisable to use the cryogenic mechanical properties of Invar® to adapt the sizing of the conduit elements in order to optimize production costs and performance.

[0051] Considering that the conduit may be exposed to varying temperatures, and that the properties of materials vary depending on the temperature to which they are exposed, the inner tube 2 according to the present invention has a thickness of 3.0 mm to 15.0 mm, for inner tubes 2 with a diameter typically comprised between 88.9 mm and 914.0 mm. This corresponds to a sizing that takes into account the physical properties of an Invar® type material at ambient or cryogenic temperatures. As previously explained, certain mechanical properties of Invar® type alloys, such as yield strength and tensile strength, are better at cryogenic temperatures than at ambient temperature. Thus, in one embodiment, considering cryogenic temperatures, the inner tube 2 has a thickness comprised between 3.0 mm and 5.0 mm. Such a thickness allows for resource savings given the improved properties of Invar® at cryogenic temperatures.

[0052] For obvious safety reasons and to ensure optimal sealing of the inner tube 2 which is in direct contact with the cryogenic fluid, it may nevertheless be preferable for the inner tube 2 to have a thickness comprised between 5.0 mm and 10.0 mm, for inner tubes 2 with a diameter typically comprised between 88.9 mm and 914.0 mm; this thickness corresponds to a sizing determined from the physical properties of the Invar® type material at room temperature.

[0053] A conduit according to the present invention comprises a second tube, called intermediate tube 3, said intermediate tube 3 being arranged around the inner tube 2. Thus, the inner wall of the intermediate tube 3 and the outer wall of the inner tube 2 define an inner annular space 6.

[0054] The intermediate tube 3 is made of a material having a low coefficient of thermal expansion, preferably a coefficient of thermal expansion less than or equal to $2.10^{-6}\,m.m^{-1}.K^{-1}$.

[0055] Thus, the material constituting the intermediate tube 3 may be an iron-nickel alloy comprising at least 34.0% nickel, preferably at least 35.0% nickel, and even more preferably at least 36.0% nickel. In a particular embodiment, the material constituting the intermediate tube 3 may be an iron-nickel alloy comprising from 34.0% to 38% nickel, preferably from 35.0% to 37.0% nickel, or even from 35.5% to 36.5% nickel. In a particularly preferred embodiment, said iron-nickel alloy comprises 36.0% nickel. In a particularly preferred embodiment, said iron-nickel alloy is Invar®.

[0056] In a preferred embodiment, the inner tube 2 and intermediate tube 3 are made of materials with identical coefficients of thermal expansion. In a further preferred embodiment, the inner tube 2 and intermediate tube 3 are made of the same material. In an even more preferred embodiment, the inner tube 2 and intermediate tube 3 are made of the same Invar®.

[0057] The intermediate tube 3 of the conduit according to the present invention has a thickness of 3.0 mm to 10.0 mm, for intermediate tubes 3 with a diameter typically comprised between 88.9 mm and 914.0 mm. Thus, in one embodiment, considering the mechanical properties at cryogenic temperatures, the intermediate tube 3 has a thickness comprised between 3.0 mm and 5.0 mm.

[0058] For the same safety reasons as those mentioned for the inner tube 2, it may nevertheless be preferable for the intermediate tube 3 to have a thickness comprised between 5.0 mm and 10.0 mm, for intermediate tubes 3 with a diameter typically comprised between 88.9 mm and 914 mm; this thickness corresponds to a sizing determined from the physical properties of the Invar® type material at room temperature.

[0059] In a particular configuration of the conduit according to the invention, the inner tube 2 and the intermediate tube 3 are made of Invar®, and said inner tube 2 has a thickness comprised between 5.0 and 10.0 mm and said intermediate tube 3 has a thickness comprised between 3.0 and 5.0 mm. That is to say, the dimensions of the inner tube 2 and intermediate tube 3 are determined taking into account the mechanical properties of Invar® at ambient temperature and cryogenic temperature, respectively. Such a configuration has the advantage of meeting safety requirements by providing a particularly large thickness for the inner tube through which the cryogenic fluid flows, while optimizing costs due to the use of less material for the intermediate tube 3. It should be considered that materials with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}\cdot K^{-1}$, in particular Invar® materials are relatively expensive compared, for example, to stainless steels, which are commonly used for cryogenics. In the event of an accidental leak from the inner tube 2 during operation, the intermediate tube 3 will then have to withstand the pressure of the cryogenic fluid while already at cryogenic temperature.

[0060] The inner annular space 6 contributes to the double confinement of the cryogenic fluid provided by the conduit according to the invention, particularly in the event of a leak or damage to the inner tube 2. It also contributes to the proper insulation of the inner tube 2. This inner annular space 6 according to the invention does not, however, comprise any thermally insulating material. In the conduit according to the invention, the inner annular space 6 is thus dedicated to preserving the integrity of the system: in particular, it allows for the implementation of one or more means enabling:

– The removal of permeant gas from the fluid flow path towards the inner annular space by pumping; the conduit is then equipped with such pumping means to evacuate the permeant gas; and/or

– Monitoring the pressure within this annular space, an increase in pressure being a sign of fluid leakage through the inner tube 2; thus, the conduit according to the

invention can be equipped with sensors enabling the detection of a pressure increase in the inner annular space 6; and/or

– The scanning of the inner annular space 6 by a carrier gas, associated with a detection, to identify more quickly any possible permeation of the cryogenic fluid towards the inner annular space; the conduit is then associated with means for circulating said carrier gas as well as possibly means for analyzing same, for example by mass spectrometry, to identify any leakage event at an early stage. In a particular embodiment, the scanning is carried out continuously and in a loop, and the pressure in the inner annular space 6 is kept sufficiently low so that there is no condensation of the cryogenic fluid transported in the inner annular space 6. It is understood that the carrier gas is selected from gases having a liquefaction temperature, at the pressure to which the inner annular space 6 is subjected, lower than that of the cryogenic fluid transported by the inner tube 2. Thus, for example, if the cryogenic fluid transported by the conduit in the lumen of the inner tube 2 is liquid hydrogen (liquefaction temperature -253°C/20 K), helium can be chosen as the carrier gas (liquefaction temperature -269°C/4.13 K).

[0061] This is not, however, incompatible with the localized presence of thermally insulating panels at certain fittings 21 as described below. The conduits 100 comprising these fittings 21 nevertheless remain made up of segments of at least 10 m, at least 50 m, at least 100 m, at least 1 km, at least 5 km, at least 10 km, at least 15 km, or even more, in which the inner annular space 6 does not comprise thermally insulating material.

[0062] A conduit according to the present invention comprises a third tube, called outer tube 4, said outer tube 4 being arranged around the intermediate tube 3. Thus, the inner wall of the outer tube 4 and the outer wall of the intermediate tube 3 define an annular space called the outer annular space 7, and the inner tube 2, intermediate tube 3 and outer tube 4 are arranged one inside the other successively.

[0063] The outer tube 4 is made of carbon steel, stainless steel, or an austenitic alloy comprising from 22 to 27% manganese by weight. The use of Invar® is possible; however, it is not necessary to ensure the safe transport of a cryogenic fluid and is currently undesirable due to the high cost of such alloys.

[0064] The outer annular space 7 of the conduit plays a crucial role in insulating the conduit and ensuring optimal conduit performance. This outer annular space 7 comprises a microporous silica-based thermal insulator 8 arranged around the intermediate tube 3 and is subjected to a reduced pressure, measured at ambient temperature, of 20.0 mbar or less, preferably 10 mbar or less, 5.0 mbar or less, 1 mbar or less, or even 0.1 mbar or less. It is understood that establishing the lowest possible pressure in the annular space 7 is particularly advantageous. Obviously, this pressure established at ambient temperature will decrease during the commissioning (or cooling) of the conduit for the transport of a

cryogenic fluid. Thus, in a particular embodiment, the pressure in the outer annular space 7, at ambient temperature, before the conduit is cooled, is comprised between 0.1 mbar and 10 mbar.

[0065] Advantageously, the microporous silica-based thermal insulation 8 is sufficiently rigid to withstand both the pressure generated by the mass of the inner tube 2 when filled with cryogenic fluid and the mass of the intermediate tube 3. This eliminates the need for additional spacers to hold the intermediate tube 3 in the outer tube 4; the insulation 8 is sufficiently resistant to act as a spacer itself between the intermediate tube 3 and the outer tube 4. In one embodiment, the microporous silica-based thermal insulation 8 has a density less than or equal to 250 kg/m^3, preferably less than or equal to 220 kg/m^3, less than or equal to 180 kg/m^3, less than or equal to 150 kg/m^3, or even less than or equal to 100 kg/m^3. In another embodiment, the silica-based microporous thermal insulation 8 has a density comprised between 40 kg/m^3 and 250 kg/m^3, between 70 kg/m^3 and 190 kg/m^3, preferably between 100 kg/m^3 and 160 kg/ m^3. In a preferred embodiment, the silica-based microporous thermal insulation 8 comprises at least 50% silica, at least 60% silica, preferably at least 70% silica. In a preferred embodiment, the silica-based microporous thermal insulation 8 is Izoflex®.

[0066] Ideally, the thickness of the inner annular space is reduced to decrease the overall size of the conduit and lower the cost of supplying steel tubes. Indeed, the cost of a steel tube is proportional to its mass, which itself depends on its diameter and wall thickness. In one embodiment, the thickness of the inner annular space is less than 100 mm, preferably less than 50 mm, or even less than 10 mm.

[0067] The thickness of the thermal insulation layer 8 is comprised between 40 and 150 mm, preferably between 50 and 120 mm, preferably between 60 and 90 mm.

[0068] Spacers can be placed between tubes 2 and 3 to allow effective welding between, on the one hand, each of the tubes 2 and, on the other hand, each of the tubes 3 of successive conduit units 1.

[0069] This arrangement, along with the nature of the tubes 2, 3, and 4, the spaces 6 and 7, and the silica-based microporous insulation 8, minimizes the mechanical and thermal stresses generated by exposure to environmental temperatures and cryogenic fluids, this allows for the design of conduit segments 100 without intermediate parts, which would further reduce these stresses by mitigating the effects of expansion and contraction. When the terrain and conduit installation conditions permit, this allows to construct conduit segments composed of several units 1, each several meters long, or even at least 10 m, 50 m, 100 m, 1 km, 5 km, 10 km, 15 km, or longer. This is particularly advantageous in terms of cost and speed of assembly. Indeed, the conduit according to the invention is an assembly of different elements, including conduit units 1 with the

structure described above and illustrated in Figure 1. These individual units 1 can have a length ranging from 10 m to 50 m. They are advantageously assembled in the workshop and transported, then used to construct the conduit on site. In segments made up of several conduit units 1, each of the tubes 2, 3, 4 of each unit 1 is simply welded end to end to form a longer segment, as shown below, while of course maintaining continuity of the lumen of the inner tube 2 and also continuity of the inner annular space 6 and the outer annular space 7, that is to say, a fitting (in particular, without fitting 20,21) in these annular spaces. Such continuity is particularly advantageous.

[0070] Thus the conduit according to the invention is advantageously made up of modular elements pre-assembled in the workshop and transported then assembled on the site of the conduit installation.

[0071] Thus, a conduit according to the invention can be an assembly of several of the following modular elements:

- conduit unit 1 as illustrated in Figure 1,
- end-piece unit 30 for a conduit as illustrated in Figure 2, which is used to close the annular spaces 6 and 7 at the ends of the conduit,
- fittings 20 or fittings 21 (illustrated in Figures 3 and 4 respectively), located at least upstream and downstream of the elbow areas in the conduit; these parts help to reduce the thermomechanical stresses that occur particularly in these regions,
- a unit bent at a specific angle which allows the direction of the conduit to be changed according, for example, to the terrain and/or constraints related to its location.

[0072] Within each of these elements there are tubes 2, 3, 4 as well as annular spaces 6, 7 which are arranged in continuity with each other in the conduit.

[0073] In addition to the conduit units 1 described above and illustrated in Figure 1, a conduit according to the present invention also comprises at least two end-piece units 30 (visible in Figure 2) at each end. This end-piece unit 30 allows the conduit ends to be sealed at the conduit termination. Advantageously, these end-piece units 30 are assembled in the workshop then transported and welded at the conduit installation site.

[0074] This end-piece unit 30 for a conduit, comprises:

- A first part 12 for closing the outer annular space 7 welded on one side to an outer tube 4 and on the other side to an intermediate tube 3, said part comprising an end of the intermediate tube 3 adapted to constitute an extension to the intermediate tube 3 of the conduit, and an end of the outer tube 4 adapted to constitute an extension to the outer tube 4 of the conduit,
- A second part 12 for closing the inner annular space 6 welded on one side to one end of the extension of the intermediate tube 3 of the part for closing the outer

annular space 7 and on the other side to the inner tube 2, said inner tube 2 comprising an end adapted to constitute an extension to the inner tube 2 of the conduit,

- in the outer annular space 7, a layer of microporous silica-based thermal insulation 8.

[0075] In one embodiment, the parts 12 for closing the outer annular space 7 and the inner annular space 6 are independently made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel®, or an austenitic alloy comprising 22 to 27% by weight of manganese. Within the same end-piece unit 30, the closing parts 12 may each be made of a material with similar (that is to say, compatible and considered close by the person skilled in the art) or identical, preferably identical, expansion properties. In a preferred embodiment, within the same end-piece unit 30, they are made of a material of identical composition. In another embodiment, the first and second closing parts are made in one piece. In this particular embodiment, said end of the inner tube 2 projects beyond the end of the intermediate tube 3, which itself projects beyond the end of the outer tube 4, so as to facilitate welding operations. In a preferred embodiment, the material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$ is an iron-nickel alloy comprising at least 34.0% nickel, preferably at least 35.0% nickel, and even more preferably at least 36.0% nickel. In a particularly preferred embodiment, said iron-nickel alloy comprises 36.0% nickel. In another preferred embodiment, it may be an iron-nickel alloy comprising from 34.0% to 38.0% nickel, preferably from 35.0% to 37.0% nickel, or even from 35.5% to 36.5% nickel. In a particularly preferred embodiment, said iron-nickel alloy is Invar®.

[0076] In a preferred embodiment, the ends of the tubes 2, 3, and 4 of the end-piece unit 30 are made of the same material as the ends of the tubes 2, 3, and 4 of the conduit to which they are intended to be welded in the method detailed below. Naturally, the dimensions of the various elements of the end-piece unit 30 are adapted to allow connection to the end of the conduit.

[0077] In a particular embodiment of the end-piece unit 30 according to the invention, a thermal insulation layer 8 is present in the inner annular space 6. This layer is intended to supplement the insulation of the conduit on the portion of the end-piece unit 30 not covered by the outer annular space 7 comprising a thermal insulation layer 8. In a preferred embodiment, this thermal insulation layer 8 present in the inner annular space 6 of the end-piece unit 30 also extends partially under the thermal insulation layer 8 of the outer annular space 7, thus providing optimal insulation at the conduit end. In other words, the thermal insulation layer 8 is located opposite the closing part 12 in the inner annular space 6.

[0078] A conduit may also include at least one elbow unit. It is readily understood that elbow units are necessary to allow the conduit to follow the defined path from point A to point B, taking into account, for example, ground conditions, by changing the conduit orientation at a defined angle. Typically, the elbow unit comprises the same elements as those described above for the conduit unit 1, except that each of the tubes 2, 3, and 4 of the same elbow unit has an identical angle comprised between 30° and 90°. Preferably, tubes 2, 3, and 4 of the elbow unit are made of the same material as the tubes 2, 3, and 4 of the conduit to which they are intended to be connected by welding in the method detailed below. Similarly, the outer annular space 7 comprises a microporous silica-based thermal insulation 8. Obviously, the diametrical dimensions of the different elements of the elbow conduit unit are adapted to the diametrical dimensions of the different conduit elements.

[0079] As mentioned, although the conduit units 1 of the conduit according to the invention are particularly suitable for limiting the thermomechanical stresses induced in the conduit, the presence of bends (in other words, areas where the conduit is curved) accentuates these stresses in the areas that contain them and makes it necessary to have fittings 20,21, as described previously in the summary, located upstream and downstream of the bends.

[0080] A fitting 20 adapted to the conduit of the invention is as described in Figure 3. This fitting 20 is advantageously assembled in the workshop then transported and welded at the conduit installation site.

[0081] Typically, the fitting 20 comprises the same elements as those described above for the conduit unit 1. Preferably, the tubes 2, 3, and 4 of the fitting 20 are made of the same material as the tubes 2, 3, and 4 of the conduit to which they are intended to be connected by welding in the method detailed below. Obviously, the diameters of the various fitting elements are adapted to the diameters of the various conduit elements to which the fitting 20 is intended to be connected.

[0082] The fitting 20 further comprises connecting parts 9 connecting the arranged tubes 2, 3, 4 in pairs, located in the outer annular spaces 7 and inner annular spaces 6. These parts are provided with at least one orifice to allow gas circulation in the annular spaces 6, 7, said parts being made of a material selected from an alloy with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, a stainless steel, Inconel®, an austenitic alloy comprising 22 to 27% by weight of manganese. In a preferred embodiment, the material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$ is an iron-nickel alloy comprising at least 34.0% nickel, preferably at least 35.0% nickel, and even more preferably at least 36.0% nickel. In a further preferred embodiment, it may be an iron-nickel alloy comprising from 34.0% to 38.0% nickel,

preferably from 35.0% to 37.0% nickel, or even from 35.5% to 36.5% nickel. In a particularly preferred embodiment, said iron-nickel alloy is Invar®. Within the same fitting 20, the connecting parts 9 may be made of a material with similar (that is to say, compatible and considered close by the person skilled in the art) or identical, preferably identical, expansion properties. In a preferred embodiment, within the same fitting 20, they are made of a material of identical composition.

[0083] As shown in Figure 3 and mentioned in the summary of the invention above, an outer additional layer 10 of thermal insulation 8 surrounded by an outer connecting tube 11 is present on this fitting 20. The outer connecting tube 11 can be made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27 % by weight of manganese. In a preferred embodiment, the outer connecting tube 11 is made of carbon steel. This fitting 20 has the advantage of being easy and quick to assemble in the workshop.

[0084] Although this fitting 20 is quite effective in mitigating the physical stresses generated at the bends in the conduit according to the invention, it may be advantageous in certain embodiments for the conduit to have no surface protrusion formed by this outer additional layer. This is made possible by the use of a fitting 21 as illustrated in Figure 4 and described in the summary of the invention above.

[0085] In the fitting 21 for the conduit according to the invention, the thermal insulation layer 8, located opposite the connecting part 9 connecting the outer tube 4 and the intermediate tube 3, is arranged in the inner annular space 6. This arrangement ensures the continuity of the outer surface of the conduit, that is to say, without any protrusions or bumps. In one embodiment, as shown in Figure 4, the thickness of the outer annular space 7 in this fitting 21 is reduced relative to the thickness of the outer annular space of the adjacent units 1. In this embodiment, this reduction allows for an increase in the inner annular space 6 to permit the localized introduction of the thermal insulation layer 8 opposite the connecting part 9 connecting the outer tube 4 and the intermediate tube 3. In this fitting 21, the highly localized presence of thermal insulation 8 does not result in a loss of the overall performance of the conduit according to the invention. Furthermore, the insulation in the inner annular space of this fitting 21 is positioned so as not to cause any particular interference with, for example, the establishment of the flow of a carrier gas through the inner annular space 6 of the conduit, as mentioned above. The compositional characteristics of the various elements of these fittings 21 are identical to those of the fittings 20. In particular, within a single fitting 21, the connecting parts 9 may be made of a material with similar (that is to say, compatible and considered close by the person skilled in the art) or identical, preferably identical,

expansion properties. In a preferred embodiment, within the same fitting 21, they are made of a material of identical composition.

[0086] In a preferred embodiment, the thermal insulation 8 is in contact with the intermediate tube and, where applicable, with regard to the fittings 20 or 21, with the outer tube or the inner tube respectively.

[0087] As mentioned, the arrangement of the conduit elements and the various modular elements act in synergy and allow to obtain a conduit that is particularly thermally efficient, safe and suitable for cryogenic fluids and more particularly for cryogenic fluids at liquefaction temperatures such as those of hydrogen or helium.

[0088] In embodiments where the connecting parts 9 and the tubes to which they are connected are made of materials with different thermal coefficients, it is advantageous to insert transition parts between the tubes and the connecting parts, these transition parts are made of a material selected from stainless steel, Inconel®, or an austenitic alloy containing 22 to 27% manganese by weight and are inserted continuously from the connecting part to the tube to which it is connected. Inconel® is known to be a superalloy highly resistant to extreme temperatures and corrosion. It contains primarily nickel, but also several other metals such as chromium, magnesium, iron, or titanium. Thus, several Inconel® alloys exist. In particular, an Inconel® within the meaning of the invention refers to a superalloy comprising at least 45% nickel such as, for example and without limitation, Supra 50®, Inconel 600, Inconel 625, or Inconel 718. An Inconel® is a material particularly preferred for transition parts, for example when a connecting part 9 is made of stainless steel and one of the tubes to which it is connected is made of Invar®.

[0089] According to another aspect, the invention also relates to the methods for assembling the above modular elements which can make up the conduit according to the invention.

Methods for assembling the various modular elements of the conduit.

[0090] Despite their triple-walled construction, the conduits 100 developed by the inventors are remarkably easy and quick to assemble. This ease and speed of assembly are due, on the one hand, to the arrangements described above and the specific choice of materials for the various components, and on the other hand, to the development of pre-assembled parts manufactured in the workshop, which can be easily transported to the conduit construction site (at sea, on land, or above ground). This ease of construction and the safety of these conduits 100 also allow to consider their installation in rugged environments or areas previously considered unsuitable for such installations. Thus, other objects of the present invention relate to methods for assembling the various modular elements mentioned above, leading to the construction of a conduit according to the invention.

[0091] Another object of the invention therefore relates to a method for assembling the conduit unit end and a conduit end-piece unit 30, which allows the inner 6 and outer 7 annular spaces to be securely sealed. This method may comprise the following steps:

- Providing a conduit unit end as described previously,
- Providing a conduit end-piece unit 30 whose inner tube 2, intermediate tube 3 and outer tube 4 are of a diameter adapted, respectively, to the extension of the inner tube 2, intermediate tube 3 and outer tube 4 of the conduit unit end,
- Welding the end of the inner tube 2 of the conduit unit 1 end with the end of the inner tube 2 of the end-piece unit 30 adapted to form an extension of the inner tube 2 of the conduit unit 1 end,
- In a space between the intermediate tube 3 of the end-piece unit 30 and the intermediate tube 3 of the conduit unit 1, inserting two intermediate half-shells made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$ and welding each one on one side to the end of the intermediate tube 3 of the end-piece unit 30 adapted to form an extension of the intermediate tube 3 of the conduit unit 1 end and on the other side to the intermediate tube 3 of the conduit unit, then welding the half-shells together,
- In the outer annular space 7, filling a space between the thermal insulation layer 8 of the conduit unit 1 end and the thermal insulation layer 8 of the end-piece unit 30, by adding a thermal insulation layer 8 in continuity with said thermal insulation layer 8 of the conduit unit 1 end and thermal insulation layer 8 of the end-piece unit 30,
- In a space between the outer tube 4 of the end-piece unit 30 and the outer tube 4 conduit unit 1 end, inserting two outer half-shells made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese and welding each one on one side to the end of the outer tube 4 of the conduit end-piece unit 30 and on the other side to the outer tube 4 of the conduit 1, then welding the half-shells together.

[0092] In a particular embodiment of the method for assembling the conduit unit end and a conduit end-piece unit 30, a thermal insulation layer 8 is present in the inner annular space 6 which extends partly under the thermal insulation layer 8 of the outer annular space 7, thus allowing optimal insulation at the end of the conduit whose inner and outer annular spaces are closed.

[0093] Another object of the invention relates to a method for assembling two ends of conduit units 1, which allows the conduit to be elongated according to the invention. This method for joining two ends of conduit unit 1 may comprise the following steps:

- Providing two ends of two units 1, whose inner tubes 2, intermediate tubes 3 and outer tubes 4 are of a diameter adapted to allow the end-to-end assembly of each of said inner tubes 2, intermediate tubes 3 and outer tubes 4 of the two units 1,
- Joining the inner tubes 2 at each end of the two conduit units 1, so that they are joined at one end.
- Welding the joined ends of the two inner tubes of each unit,
- Joining the intermediate tubes 3 of each unit to the ends of the intermediate tubes 3 of each unit so that they are joined and form a single tube surrounding the inner tube 2,
- Welding the joined ends of the intermediate tubes 3 of each of the units,
- Ensuring the continuity of thermal insulation in the outer annular space 7, for example, by adding thermal insulation 8 in the outer annular space 7 at the junction of the two units,
- Joining the outer tubes 4 of each unit to the ends of the outer tubes 4 of the units, so that they are joined and form a single tube surrounding the inner tube 2,
- Welding the joined ends of the outer tubes 4 of each of the units.

[0094] Advantageously, the thermal insulation layer 8 of the outer annular space 7, by virtue of its resistance, allows to maintain the necessary space between intermediate tubes 3 and outer tubes 4 of each of the units during the step of welding the intermediate tubes 3 to each other and the tubes 4 to each other.

[0095] Another object of the invention relates to a method for assembling the conduit unit 1 end and a fitting 20,21 of a conduit 1, said fitting comprising:

- three tubes arranged one inside the other 2, 3, 4:
  - an inner tube 2 made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}\,m.m^{-1}.K^{-1}$
  - an intermediate tube 3 made of a material with a coefficient of thermal expansion less than or equal to $2.10^{-6}\,m.m^{-1}.K^{-1}$
  - an outer tube 4 made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese

  said three tubes arranged one inside the other 2, 3, 4 defining an inner annular space (6) comprised between said inner tube 2 and said intermediate tube 3 and an outer annular space 7 comprised between said intermediate tube 3 and said outer tube 4, the outer annular space 7 comprising a microporous silica-based thermal insulation 8,
- connecting parts 9 connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer annular spaces 7 and inner annular spaces 6, provided with at least one orifice so as to allow the circulation of gas in the

annular spaces 6, 7, said parts being made of an alloy with a coefficient of expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising from 22 to 27 wt% of manganese,

in the case of connecting parts 9 connecting tubes made of materials with different thermal coefficients, tubular transition parts are positioned between the connecting parts 9 and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part (9) and the tube on which it is positioned,

- at the connecting part 9 connecting said outer tube 4 and said intermediate tube 3:
    - an outer additional layer 10 of microporous silica-based thermal insulation 8, surrounded by an outer connecting tube 11 made of carbon steel, stainless steel, or austenitic alloy comprising 22 to 27 % by weight of manganese, said outer connecting tube 11 being welded at its ends to the outer tube 4 of the fitting, or
    - a thermal insulation layer 8 opposite said connecting part 9 is located in the inner annular space 6,

The method comprising the following steps:

- Providing one conduit unit 1 end comprising three tubes arranged one inside the other 2, 3, 4:
    - an inner tube 2 made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
    - an intermediate tube 3 made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
    - an outer tube 4 made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

  said three tubes arranged one inside the other 2, 3, 4 defining an inner annular space (6) comprised between said inner tube 2 and said intermediate tube 3 and an outer annular space 7 comprised between said intermediate tube 3 and said outer tube 4, the outer annular space 7 comprising a microporous silica-based thermal insulator 8, the inner annular space 6 not comprising any insulating material,

- Providing the fitting 20,21 of the conduit 1, whose inner tube 2, intermediate tube 3 and outer tube 4 are of a diameter adapted, respectively, to the extension of the inner tube 2, intermediate tube 3 and outer tube 4 of the conduit unit 1 end,

- Welding the end of the inner tube 2 of the conduit unit 1 with the end of the inner tube 2 of the fitting 20,21 of the conduit 1,
- In a space between the intermediate tube 3 of the fitting 20,21 of the conduit 1 and the intermediate tube 3 of the conduit unit 1 end, inserting two intermediate half-shells made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$ and welding each of them on one side to the end of the intermediate tube 3 of the fitting 20,21 of the conduit 1 and on the other side to the intermediate tube 3 of the end of the conduit unit 1, then welding the half-shells together,
- In the outer annular space 7, filling a space between the thermal insulation layer 8 of the conduit unit 1 end and the thermal insulation layer 8 of the conduit 1 fitting 20,21, by adding a layer of insulation 8 in continuity with said thermal insulation layer 8 of the conduit unit 1 end and thermal insulation layer 8 of the conduit 1 fitting 20,21,
- In a space between the outer tube 4 of the fitting 20,21 and the outer tube 4 of the conduit unit 1, inserting two outer half-shells made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese and welding each one on one side to the end of the outer tube 4 of the fitting 20,21 for conduit 1 and on the other side to the outer tube 4 of the conduit unit 1 end, then welding the half-shells together.

[0096] The half-shells are sized to allow the joining of the tubes they are intended to connect; they are shaped like half-cylinders (or half-tubes). They allow the conduit to be closed according to the invention. In a particular embodiment, the half-shells are made of the same material as the tubes to which they are connected.

[0097] In a particular embodiment, each, independently of the methods detailed above, may comprise the non-destructive testing of at least one weld carried out therein.

Claims

Claim 1.A conduit adapted for transporting a cryogenic liquid, thermally insulated, **characterized in that** it comprises

- three tubes arranged one inside the other (2, 3, 4):
  - an inner tube (2) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an intermediate tube (3) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an outer tube (4) made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

    said three tubes arranged one inside the other (2, 3, 4) defining an inner annular space (6) comprised between said inner tube (2) and said intermediate tube (3) and an outer annular space (7) comprised between said intermediate tube (3) and said outer tube (4),

    the outer annular space (7) comprising a microporous silica-based thermal insulator (8), the inner annular space (6) not comprising any thermal insulating material,
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27 wt% manganese,

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

Claim 2.A unit (1) of conduit adapted for transporting a cryogenic liquid **characterized in that** it comprises:

- three tubes arranged one inside the other (2, 3, 4):
  - an inner tube (2) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,

- an intermediate tube (3) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
- an outer tube (4) made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,

- said three tubes arranged one inside the other (2, 3, 4) defining an inner annular space (6) comprised between said inner tube (2) and said intermediate tube (3) and an outer annular space (7) comprised between said intermediate tube (3) and said outer tube (4),
- the outer annular space (7) comprising a microporous silica-based thermal insulator (8), the inner annular space (6) not comprising any thermal insulating material,
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27% by weight of manganese,

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

Claim 3. A fitting (20) for a conduit according to claim 1 **characterized in that it comprises:**

- three tubes arranged one inside the other (2, 3, 4):
  - an inner tube (2) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$
  - an intermediate tube (3) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$
  - an outer tube (4) made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese

said three tubes arranged one inside the other (2, 3, 4) defining an inner annular space (6) comprised between said inner tube (2) and said intermediate tube (3) and an outer annular space (7) comprised between said intermediate tube (3) and said outer tube (4),

the outer annular space (7) comprising a microporous silica-based thermal insulator (8),

- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, provided with at least one orifice so as to allow the circulation of gas in the annular spaces (6, 7), said parts being made of an alloy with a coefficient of expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising from 22 to 27 wt% of manganese),

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts are positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part (9) and the tube on which it is positioned,

- at the connecting part (9) connecting said outer tube (4) and said intermediate tube (3), an outer additional layer (10) of microporous silica-based thermal insulation (8), surrounded by an outer connecting tube (11) of carbon steel, stainless steel, or austenitic alloy comprising 22 to 27 % by weight of manganese, said outer connecting tube (11) being welded at its ends to the outer tube (4) of the fitting.

Claim 4. The fitting (21) for a conduit according to claim 1 **characterized in that it comprises:**

- three tubes arranged one inside the other (2, 3, 4):
  - an inner tube (2) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$
  - an intermediate tube (3) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$
  - an outer tube (4) made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese

said three tubes arranged one inside the other (2, 3, 4) defining an inner annular space (6) comprised between said inner tube (2) and said intermediate tube (3) and an outer annular space (7) comprised between said intermediate tube (3) and said outer tube (4),

the outer annular space (7) comprising a microporous silica-based thermal insulator (8),

- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, provided

with at least one orifice so as to allow the circulation of gas in the annular spaces (6, 7), said parts being made of an alloy with a coefficient of expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising from 22 to 27 wt% of manganese,

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts are positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part (9) and the tube on which it is positioned,

- at the connecting part (9) connecting said outer tube (4) and said intermediate tube (3), a thermal insulation layer (8) opposite said connecting part (9) is located in the inner annular space (6).

Claim 5. An end-piece unit (30) for a conduit according to claim 1, the end-piece unit (30) characterized in that it comprises:

- a first part (12) for closing the outer annular space (7) welded on one side to an outer tube (4) and on the other side to an intermediate tube (3), said part comprising an end of the intermediate tube adapted to constitute an extension to the intermediate tube (3) of the conduit, and an end of the outer tube adapted to constitute an extension to the outer tube (4) of the conduit, said part being made of an alloy with a coefficient of expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising 22 to 27% by weight of manganese,
- a second part (12) for closing the inner annular space (6) welded on one side to one end of the extension of the intermediate tube (3) of the part for closing the outer annular space (7) and on the other side to the inner tube (2), said inner tube (2) comprising an end adapted to constitute an extension to the inner tube (2) of the conduit, said part being made of an alloy with a coefficient of expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, of Inconel®, or of an austenitic alloy comprising from 22 to 27 wt% of manganese,
- in the outer annular space (7), a layer of microporous silica-based thermal insulation (8),
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of

thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27% by weight of manganese,

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

Claim 6. An elbow unit for a conduit according to claim 1, the elbow conduit unit comprising:

- three tubes arranged one inside the other (2, 3, 4):
  - an inner tube (2) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an intermediate tube (3) made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$,
  - an outer tube (4) made of carbon steel, stainless steel, or an austenitic alloy comprising 22 to 27% by weight of manganese,
- said three tubes arranged one inside the other (2, 3, 4) defining an inner annular space (6) comprised between said inner tube (2) and said intermediate tube (3) and an outer annular space (7) comprised between said intermediate tube (3) and said outer tube (4),
- the outer annular space (7) comprising a microporous silica-based thermal insulator (8),
- said tubes arranged one inside the other (2, 3, 4) having a curvature at an angle comprised between 30° and 90°
- connecting parts (9) connecting said three tubes arranged one inside the other (2, 3, 4) in pairs, located in the outer (7) and inner (6) annular spaces, and provided with at least one orifice to allow the circulation of gas in the inner (6) and outer (7) annular spaces, said parts being made of a material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$, of stainless steel, Inconel® or an austenitic alloy comprising 22 to 27% by weight of manganese,

in the case of connecting parts (9) connecting tubes made of materials with different thermal coefficients, tubular transition parts positioned between the connecting parts (9) and at least one of the two tubes, said transition parts being made of a material with a thermal coefficient intermediate to that of the connecting part and the tube on which it is positioned.

Claim 7. The conduit according to claim 1, the conduit unit (1) according to claim 2, the fitting (20,21) according to claim 3 or 4, or the end-piece unit (30) according to claim 5, wherein the material with a coefficient of thermal expansion less than or equal to 2.10^{-6} $m.m^{-1}.K^{-1}$ constituting the inner tube and/or the intermediate tube is an iron-nickel alloy comprising 34.0% to 38.0% nickel, preferably 35.0% to 37.0% nickel, or even 35.5% to 36.5% nickel.

Claim 8. The conduit according to any one of claims 1 or 7, or the fitting (20,21) according to any one of claims 3 or 4, or the end-piece unit (30) according to claim 5, wherein, respectively, the connecting parts (9) or closing parts (12) are made of an iron-nickel alloy comprising 34.0% to 38.0% nickel, preferably 35.0% to 37.0% nickel, or even 35.5% to 36.5% nickel.

Claim 9. The conduit according to claim 1, characterized in that it comprises a segment of at least 10 m, preferably of at least 50 m, preferably of at least 100 m, preferably of at least 1 km, preferably of at least 5 km, preferably of at least 10 km, or even preferably of at least 15 km in which the outer 7 and inner 6 annular spaces do not contain a fitting (20,21) according to claim 3 or 4.

Claim 10. The conduit according to claim 1, characterized in that when it comprises an elbow conduit unit according to claim 6, a fitting (20,21) of a conduit (1) according to claim 3 or 4 is placed upstream and/or downstream of said elbow conduit unit.

Claim 11. The conduit according to claim 1 characterized in that the microporous thermal insulation (8) has a density comprised between 40 $kg.m^{-3}$ and 250 $kg.m^{-3}$, between 70 $kg.m^{-3}$ and 190 $kg.m^{-3}$, preferably between 100 $kg.m^{-3}$ and 160 $kg.m^{-3}$.

Claim 12. The conduit according to claim 1 wherein a gas is circulated in the inner annular space (6), said gas having, at the circulation pressure in the inner annular space, a liquefaction temperature lower than that of the cryogenic liquid transported in the conduit (1).

Claim 13. The conduit according to claim 12, at one end of which is coupled at least one means for analyzing the gas circulating in the inner annular space (6).

Claim 14. The conduit according to any one of the preceding claims wherein the pressure in the outer annular space (7), at ambient temperature, before the conduit is cooled, is less than or equal to 10 mbar.