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MONITORING OF CRYOGENIC FLOWS: REALIZATION OF THE RADIO FREQUENCY METHOD

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INTRODUCTION

"Over 90% of all measurements are temperature, pressure, level and flow rate measurements" [1]. This also applies to cryogenics, where the correct choice of cryogen parameters determines safety and efficiency of research and industrial installations. Cryogens are quite often used in a two-phase state or in the form of a 2-component or 3-component mixture; so, besides the parameters mentioned, it is necessary to determine phase ratio characteristics (local and average vapour content, concentrations, flow patterns). It should also be mentioned that some specific features of cryogenic systems and cryogens impose significant restrictions on the measuring equipment.

Besides low temperature, the specific features affecting the choice of the principle of operation and the design of the sensor for cryogenic systems are:

1. Relatively difficult replacement and size limits. So the sensitive element of the sensor must be small in size and sufficiently reliable, which is achieved owing to a simple design without moving parts;

2. Possible transitions from two-phase to single-phase flows. In this connection, one should choose at least one quantity carrying information about both single-phase and two-phase states of a fluid as a measured (signal) characteristic of a flow;

3. Significant difference between the physical properties of cryogens and the properties of phases, which is usually observed in practice. Helium is a typical example: two-phase HEI [2] and especially HeII - gas flows [3].

A helpful tool for diagnostics of both two-phase flows and single-phase flows close to saturation is a resonance radio frequency sensor [4]. Its signal characteristic depends on the dielectric constant of the medium ε. In a two-phase vapour-liquid medium the dielectric constants of the phases ε_l and ε_g depend on the saturation pressure P_s. So, measuring P_s (or T_s) and ε one can obtain information on the qualitative ratios of phases in the flow, both local $\varphi_{loc}=\varphi(\vec{r})$ and average $\varphi=\langle\varphi(\vec{r})\rangle=A_g/(A_g+A_l)$. As it is shown below, the void fraction φ and the quality $x=G_g/(G_g+G_l)$ are connected to each other through simple relations. It allows determination of mean flow-rate thermodynamic characteristics: enthalpy $i=i_g x+i_l(1-x)$, entropy $s=s_g x+s_l(1-x)$, etc. In a single- phase region the quantities P and ε unambiguously identify the thermodynamic state of a fluid and, like P and T, they allow determination of other thermophysical characteristics. The analysis shows that RF sensors can comply with the above-mentioned specific features of cryogenic measurements. This paper deals with cryogenic applications of intelligent RF sensors alone and in combination with other devices for determination of qualitative and quantitative characteristics of cryogens.

SENSITIVE ELEMENTS

The output parameter of an RF sensor is the resonance frequency f, which is defined in a general case as [4] $f^2=f_0^2\left(1+\int \varepsilon(\vec{r})E^2(\vec{r})\,d\vec{r}/\int E^2(\vec{r})\,d\vec{r}\right)$ where f_0 and $\vec{E}$ are the resonance frequency and the electric field strength of the sensor "filled" with vacuum. Thus, the quantity f depends not only on the mean integral dielectric constant of the flow but also on the distribution of phases over the channel cross section. So, by exciting oscillations with different configurations of the electric field $\vec{E}(\vec{r})$, one can both determine the mean characteristics and study the fine structure of the flows. Let us consider two examples involving measuring resonators with annular or circular channels.

<u>Sensor with an annular channel</u>. If there is an annular channel, it seems to be reasonable to use a sensor in the form of a short-circuited coaxial resonator with inductive excitation of oscillations (Fig.1). When the first harmonic of class TEM oscillations is excited in the resonator, the electric field strength between the channel walls varies logarithmically, and at a sufficiently small value of δ/d_{in}

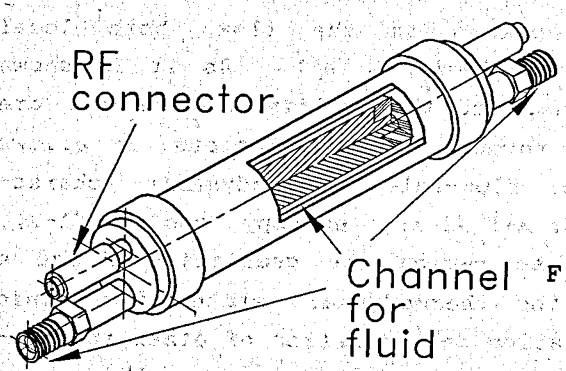

Fig. 1. Sensor with channel of annular cross-section.

the field is close to the uniform one. The length l_s of the sensitive element must satisfy the resonance conditions and be relatively large ($l_s \ll d_{in}$) to reduce nonlinear edge effects. Uniformity of the field allows measurement of the cross-section mean dielectric constant and thus the void fraction of flow φ. By exciting oscillations of higher harmonics in the resonator, one can obtain more complicated configurations of the electric field. Analyzing a series of resonance frequencies of the first and higher harmonics f_0, f_1, ..., f_n, one can obtain information on the phase distribution structure in the flow on the basis of the relevant algorithms.

<u>Sensor with a round channel</u>. A sensor with a round channel is an open resonator with capacitive excitation of

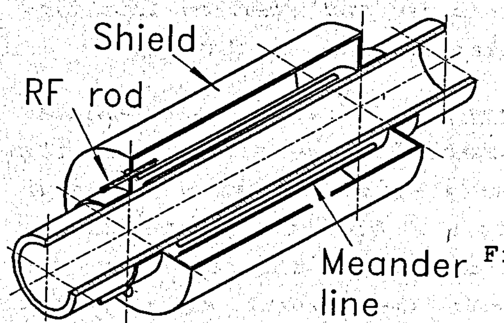

Fig. 2. Sensor with channel of round cross-section.

oscillations. A long meander-type line is applied to the external surface of a dielectric tube that serves as a measuring channel [4]. When a resonance of the first-mode oscillations (of the dipole type) is excited in the line, the potential distribution over the tube surface is close to the harmonic one. If the sensor is sufficiently long and the meander pitch is sufficiently small, there is a highly uniform field in the measuring volume. So, as in the previous case, the measurement at the first harmonic of TEM oscillations allows one to determine the mean dielectric constant of the flow. Yet, there are some difficulties arising from the fact that even an ideal uniform field is distorted by a nonuniform dielectric, and the resonance frequency f thus depends on orientation of the phase boundaries with respect to the direction of E. It is best manifested in stratified flows or flows close to stratified ones.

There are two ways to decrease the corresponding error. 1- Using a twisted meander. In a sensor of this design (see Fig.3a) much of the error is automatically corrected. Yet, the twisted meander sensor can be mainly used to determine integral characteristics. 2- Using several pairs of communication rods (see Fig.3b). The resulting value of φ is calculated as a mean $\varphi=\varphi(\varphi_1,\varphi_2,...,\varphi_n)$ of the values of φ_i obtained for each pair of rods. A sensitive element with several pairs of exciting and detecting rods allows development of a device for investigations of the internal flow patterns in a round channel. Analyzing the first harmonic frequencies $f_{01},f_{02},...,f_{0n}$ of the resonator for different pairs of rods and similar frequency sets $f_{11},f_{12},...,f_{1n}$; $f_{m1},f_{m2},...,f_{mn}$ of higher harmonics, one can reconstruct the two-dimensional pattern of the phase distribution in the flow in some approximation, using mathematical methods of tomography. This design of a "dielectric tomographer" resembles the "flow image" capacitive device presented in ref.[6]. However, the use of a resonator instead of a multiplate capacitor [5] allows to obtain a higher accuracy of

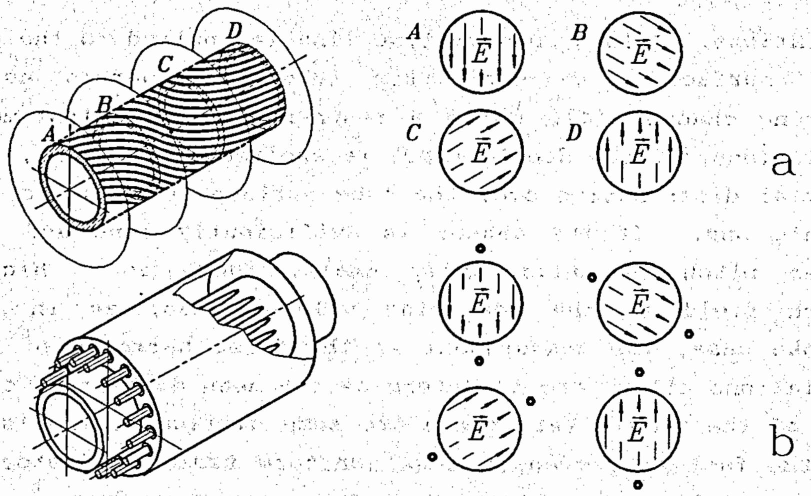

Fig.3. Sensors with a twisted meander and several pairs of rods.

measurement and more information, since a resonator tomographer has two information channels, one being different pairs of rods, the other being different harmonics, while in the capacitive device there are only different combinations of pairs of plates.

The calculations and the experiments performed by the authors [6] show that RF sensors used for void fraction measurements of cryogen flows allow in principle a very high accuracy, the methodical (unavoidable) error related to the field and phase distribution nonuniformity being ≤2.5%. Yet, the actual error can be larger mainly because of inaccurate evaluation of φ by the resonance frequency f and pressure P, i.e. because of calibration errors. Besides, in many cases the measurements are aimed at finding the quality x and not φ, the interrelation of these quantities being determined by the flow hydrodynamics. These two important problems of measurement analysis are dealt with in the next section.

INTERPRETATION OF MEASUREMENT

<u>Calibration</u>. The calibration of a radio frequency VF sensor with a uniform energy distribution of the electric

field consists in determining the dependence of the resonance frequency f on the dielectric constant ε of the medium in the sensor. In a wide variation range of ε this problem can probably be solved only experimentally or, in some cases, by numerical simulation. Yet, in the practically important pressure interval the difference in vapour and liquid dielectric constants of different cryogenic media is comparatively small. For example, at P=100 kPa we have $(\varepsilon_l-\varepsilon_g)/\varepsilon_l\cong0.04$ for helium, $(\varepsilon_l-\varepsilon_g)/\varepsilon_l\cong0.18$ for hydrogen, $(\varepsilon_l-\varepsilon_g)/\varepsilon_l\cong0.29$ for nitrogen (here ε_l and ε_g are the dielectric constants of the liquid and gaseous cryogens in the saturation line). Our measurements showed that the relative variation of the resonance frequency $(f_l-f_g)/f_l$ in the φ interval from 0 to 1 is not large either*. On the other hand, to choose an approximation, which is valid with the prescribed degree of accuracy in a small variation interval of the argument ε and the function f, is quite a solvable problem. It can be done by fixing the form of the function with several coefficients that can be found from the experimental data. One can solve the function $f(\varepsilon)$, for example, as a power series in $\Delta\varepsilon=\bar{\varepsilon}-\varepsilon_l$: $f(\bar{\varepsilon})=f(\varepsilon_l+\Delta\varepsilon)=f_l+a_1\Delta\varepsilon+a_2(\Delta\varepsilon)^2+a_3(\Delta\varepsilon)^3+\dots$. However, there seems to be a more preferable way when the resonator is replaced by an equivalent circuit with the concentrated parameters, which allows a physically substantiated form of the function $f(\varepsilon)=F_{phy}(\varepsilon,K_1,K_2,\dots,K_n)$ with a set of experimentally determinate coefficients $K_1,K_2,\dots,K_n$. The coefficients K_i are determined by the measurements of resonance frequencies f_i while one fills the sensor with media of known dielectric constants ε_i. Compared with the previous approach, this one must ensure the prescribed accuracy at a much smaller number of coefficients, which is proved by the experiments with helium and nitrogen. In Fig.4 there is the

*As pointed out in ref.[6], the value of $(f_l-f_g)/f_l$ for helium is ≅ 0.016, which makes the requirements to the measuring equipment more stringent.

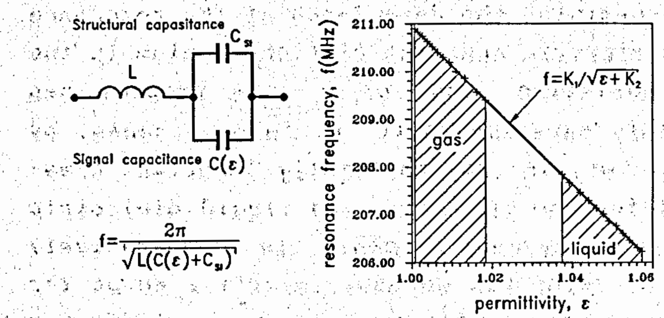

Fig. 4. Equivalent circuit and calibration curve of annular sensor for Helium.

simplest equivalent circuit of an annular sensor and the corresponding calibration curve $f(\varepsilon) = K_1/(\varepsilon+K_2)^{0.5}$. The coefficients K_1 and K_2 were calculated after processing a set of the experimental data obtained while the sensor was filled with liquid and gaseous helium in the saturation line at pressures 50 kPa $\leq P \leq$ 210 kPa. The variation interval of ε, "directly" measured during the calibration, appears to be 2/3 of the whole signal range of the measurements. The adequacy of the calibration function in the whole range is proved by the experiments, when the quantity φ was determined by the saturated helium and nitrogen filling level of the sensor.

Proceeding from the calibration function of the sensor filled with a single-phase fluid $f=f(\varepsilon)$ to the functions $\varphi=\varphi(f)$ for a two-phase flow, we assume that $\varepsilon=\varphi\varepsilon_g+(1-\varphi)\varepsilon_1$, which is a fairly accurate assumption for cryogenic fluids $(\varepsilon_1-\varepsilon_g)/\varepsilon_1 \ll 1$. With this assumption, the calibration function $\varphi(f)$ for an annular sensor takes on the form $\varphi = (\varepsilon_1-(K_1^2/f^2-K_2))/(\varepsilon_1-\varepsilon_g)$. Fig.5 shows the calibration functions for three cryogens. One can see that the functions $\varphi(f)$ are close to linear ones. More accurate calibration characteristics can be obtained through numerical calculation of the resonators. The methods and software for this calculation are well developed.

<u>Determination of flow-rate related quality</u>. In the general case, because of different flow patterns, the quantity

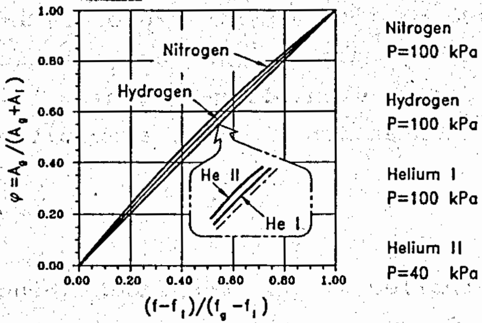

Fig. 5. Calibration functions for some cryogens.

x bears a sophisticated relationship to φ, flow mass velocity m, geometric characteristics of the channels and physical properties of the phases: densities ρ_1, ρ_g, viscosities μ_1, μ_g... . Yet one can find the regions where x and φ are connected by a simple relationship. In horizontal flows, for example, one can single out two regions: the low mass velocity region of stratified flows and the high mass velocity region of homogenized flows. At relatively large m the channel orientation does not matter and the function $x(\varphi)$ for homogenized flows can apply to vertical channels as well. The boundaries of the regions and the types of the relations $x=x(\varphi)$ in each of them are considered, for example, in ref.[7], and for two-phase helium flows in ref.[2]. For example, for narrow rectangular or annular channels with helium $x(\varphi)$ functions are determined as follows: $x_s=\varphi/((\rho_1/\rho_g)^{4/7}(\mu_g/\mu_1)^{1/7}(1-\varphi)+\varphi)$ in the case of stratified flows, and $x_n=\varphi/((\rho_1/\rho_g)(1-\varphi)+\varphi)$ in the case of homogenized flows. In ref.[6] it is shown that the above functions are in good agreement with the experimental results. Thus, when the void fraction φ is known, the quantity x for hydrodynamically stabilized flows can be unambiguously determined by simple formulae, if the flows are definitely stratified or homogenized. However, none of these formulae can be absolutely accurate, which increases the error of determination of x as compared with the error $\delta\varphi$. As a result, δx may amount, e.g. for helium, to ≈5-7%.

As it seen from the above stated, the RF sensor signal processing requires electronic computer means. Suitable for this procedure are specially designed intelligent controllers with standard interfaces for connection to data acquisition and processing systems.

INTELLIGENT CONTROLLERS

A general view of a controller as an independent block is given in Fig.6. The block-diagram of this device is shown in Fig.7. The device is structurally divided into two modules - a measuring and a processing one. The measuring module consists of a sweep generator (*SG*), an extreme regulator (*ER*), *RF* commutators, a commutator of analogue signals, a 10-bit *ADC* (for pressure measurement). To determine the resonance frequency, the *SG* sends a signal to the sensor. From the sensor the frequency signal goes to the extreme regulator, which controls the sweep generator and maintains the resonance frequency f. From the second output of the *SG* the signal is applied to a frequency meter consisting of two counters (f and f_{ref}). To achieve a higher count accuracy, the frequency variation period is chosen to be a multiple of

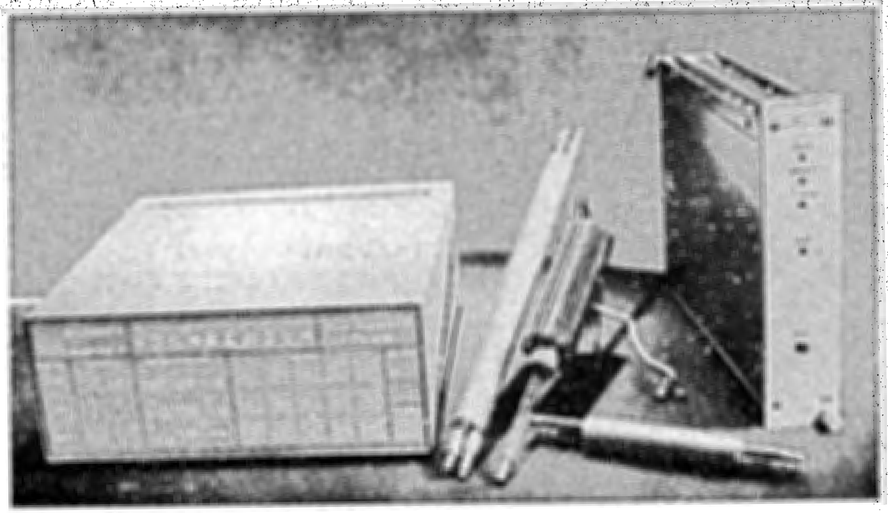

Fig. 6. General view of intelligent controllers and void fraction sensors.

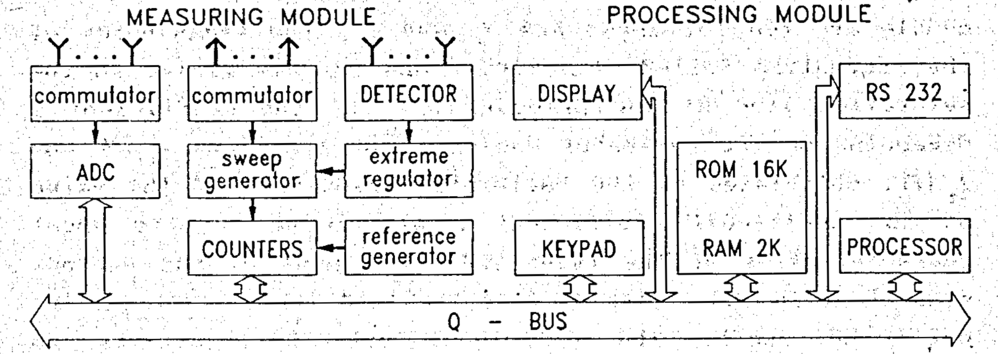

Fig. 7. The block-diagram of the independent controller.

the *ER* gating period. The processing module is based on a 16-bit single-chip discharge microprocessor K1801BM2, which has a fixed instruction set compatible with that of the single-board computer *LSI*-11. The processing module board is a functionally complete microcomputer with a processor, 16K *ROM*, 2K *RAM*, a serial interface controller, an alphanumeric display controller, a function keyboard controller, a controller for connection to the measuring module, a start register.

We shall explain the operation of the device considering the front panel shown in Fig.8. The controller has two modes - adjustment and measurement. In the adjustment mode the reference parameters of the resonators connected to the

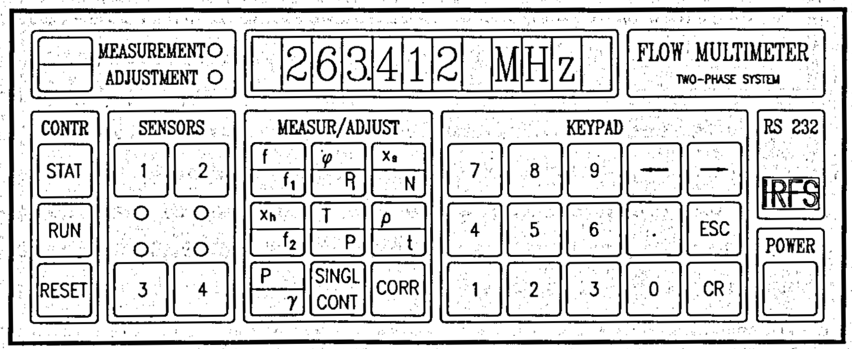

Fig. 8. Front panel of the independent controller.

module are fed in. These are f_1 and f_2, the frequencies of the resonators filled with liquid and gaseous fluids in the saturation line at the pressure P_1, and the coefficient γ depending on the resonator design. The functions $f_1(P)$ and $f_2(P)$, calculated by the calibration results, and the value of the additional coefficient γ are given as data sheet characteristics of the resonator. The input of the current pressure P in the system is also provided (if an analogue input is not used). The following measurement parameters are also set in the adjustment mode: single/continuous, t - time of single measurement, N - number of single measurements in a series. The parameters N and t allow averaging of the measured characteristic over the time interval t or statistical analysis of a sample of N measurements. In the measurement mode the characteristic to be measured is chosen: f - resonance frequency; φ - void fraction; x_h and x_s - the quality of a homogenized or a stratified flow; T - temperature; ρ - density; P - pressure. The buttons of the field "contr" have the following functions. Pressing the "stat" button one scrolls the reference quantities and mode parameters of the device. The "run" button starts measurements (it is only used for single measurements), and the "reset" button switches on the default reference quantities and modes of operation. The software is written in the Assembler language. To calculate properties in the single-phase and two-phase regions, interpolation by specially organized tables of thermodynamic properties stored in *ROM* is used. At present there are programs for calculation of Helium, Nitrogen, Hydrogen flow parameters. The fluid is selected by a switch on the rear panel. There are also input and output *RF* connectors, analogue input connectors for pressure sensor signals. The device can be controlled either manually or through the *RS*-232 interface. Four sensors can be connected to the device.

Another version of the intelligent controller is made to the CAMAC standard (Fig.6). Its structure is similar to that of the independent controller considered. Control, data

input and output are carried out through the CAMAC bus. On the front panel there are an error indicator and a reset button. A block controlled both through the front panel and through the bus is also developed. Two resonators are connected to this controller. This block calculates fewer characteristics than the independent one because further analysis of the data can be performed by the computer controlling the crate.

POSSIBLE APPLICATIONS AND SENSOR CONNECTIONS

<u>Measurement of vapour-liquid expander efficiency and JT-valve setting</u>. The possibility of unambiguously determining the flow quality naturally prompts one to use the RF sensors at the final cooling stages of cryogenic installations. We use the sensor and the intelligent controller, for example, to determine rapidly (the measurement time was from 20 to 200 ms) the cooling capacity of a 300 W refrigerator at 4.5 K, as shown in Fig.9. Three methods were employed to measure the capacity in the liquefying mode at the flow rate $(13\text{-}20)\cdot 10^{-3}$ kg/s: by means of a level meter, by means of a void fraction sensor, and by P & T values in front of the *JT*-valve. The results obtained are in good agreement with each other. The discrepancy is within 2-9%, which is due to the orifice plate and the RF sensor calibration errors and to possible partial

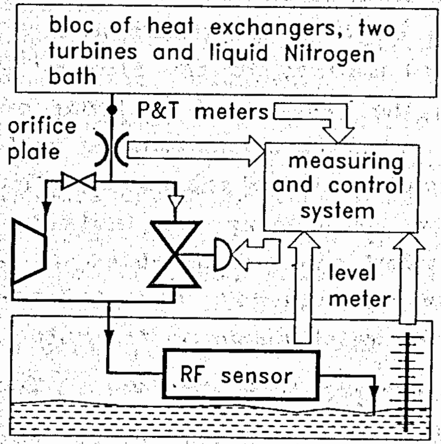

Fig. 9. Applications of void fraction sensor in refrigerator.

entrainment of liquid helium in the reverse flow. Besides the void fraction sensor is used to determine the thermodynamic efficiency of a vapour-liquid turbine where it seems to be indispensable (the turbine was manufactured at the SKIF factory, Moscow).

Our experience indicates that *RF* sensors are valuable measuring devices for automatic regulation systems in cryogenic installations, producing a relatively fast effect on a regulator after a possible disturbance.

<u>Flow rate measurement</u>. When the single-phase flow rate is determined by the pressure difference ΔP in a narrowing device $G=\xi(\rho\ \Delta P)^{0,5}$ or by the number of turbine revolutions n $G=\xi\rho n$, the *RF* sensor can serve as mean density meter. So one of the necessary parameters determined by the intelligent device is the mean density ρ.

The two-phase flow rate can also be determined by the pressure difference at the orifice plate [8] or by the number of turbine revolutions n [7]. In this case, however, the flow rate G is involved in sophisticated relations $G = G(\Delta P, x$, thermophysical properties) or $G=G(n, x$, thermophysical properties) and the *RF* sensor is to be used for estimation of x. The correlation and tagging methods or their combination seem to be more preferable for determination of the two-phase flow rate (see Fig. 10). When we used these methods with *RF* sensors, the tags were heat pulses applied to the flow by a heater placed at a distance from the sensor and in front of it. The device is based on the intelligent controller with an additional data processing algorithm. For the correlation measurements of the flow rate two *RF* sensors are installed one after another in the flow (they can be assembled as a single structural unit). Their frequency signals are processed by one intelligent block, which computes the mutual correlation function $R_{12}(\tau) = \frac{1}{T}\int_0^T \varphi_2(t)\varphi_1(t-\tau)\,dt$. The flow rate is calculated as $G=\beta\rho SL/\tau_c$, where β is the

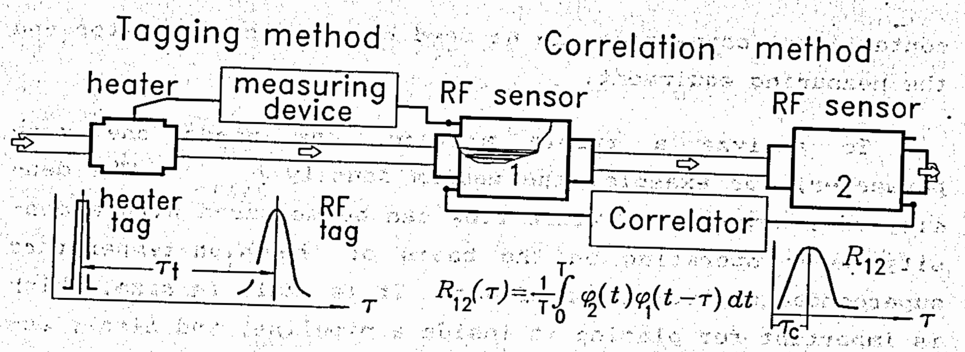

Fig. 10. Determination of the two-phase flow rate.

correction coefficient, S is the channel cross section, L is the distance between the sensors, τ_c is the time for which R_{12} has the maximum value. A flowmeter of this type on the basis of the independent controller described in the previous section is also being developed now. For any pair (in the set of 4 sensors) there is a possibility of calculating the mutual correlation function and the mass flow rate. The preliminary experiments showed that the accuracy of the two-phase helium flow rate measurement by the tagging and correlation methods is noticeably higher as compared with the calorimetric measurement [6] or measurement with a flowmeter based on an orifice plate and a void fraction sensor.

<u>Determination of concentrations of binary and triple mixtures</u>. The dielectric constant of a binary mixture ε_{bin} depends on the concentration of components ζ and on their dielectric constants ε_1 and ε_2: $\varepsilon_{bin}=\varepsilon_{bin}(\zeta,\varepsilon_1,\varepsilon_2)$. In their turn, the dielectric constants are state functions $\varepsilon_1=\varepsilon_1(P,T)$, $\varepsilon_2=\varepsilon_2(P,T)$. Thus, measuring the pressure P, the temperature T and the dielectric constant of the flow with RF sensors, one can find the dielectric constant of a binary mixture and, consequently, its concentration. In cryogenics, for example, a $^3He+^4He$ solution is used to obtain very low temperatures. Miniature *RF* sensors can be a suitable tool for determining concentrations of components. To avoid heat input through *RF* cables a capacitive, i.e. completely

contactless, connection can be used between the resonator and the measuring equipment.

To analyze a triple mixture, one needs one more parameter, for example, the medium density ρ_{trip}. The density of a cryogenic mixture flow can be measured with a density meter operating on the basis of the high-temperature superconductor levitation effect. It is small in size, which is important for placing it inside a pipeline, and highly accurate ($\delta\rho \leq 0.06\%$). Concentrations of components ζ_1, ζ_2, ζ_3 are found by solving the set of three equations

$$\begin{cases} \varepsilon_{trip} = \varepsilon_{trip}(\zeta_1, \zeta_2, \zeta_3, \varepsilon_1(P,T), \varepsilon_2(P,T), \varepsilon_3(P,T)) \\ \rho_{trip} = \rho_{trip}(\zeta_1, \zeta_2, \zeta_3, \rho_1(P,T), \rho_2(P,T), \rho_3(P,T)) \\ \zeta_1 + \zeta_2 + \zeta_3 = 1 \end{cases}$$

Though at first glance this way of analysis seems to be sophisticated sometimes it can be much simpler and cheaper than traditional chromatography.

CONCLUSION

To monitor cryogen flows, it is convenient to use a radio frequency method, which involves a signal capacitor connected to an oscillator circuit whose resonance frequency depends on the dielectric constants of cryogens. This method has the following advantages:

- high accuracy due to a specific design and low-temperature calibration;
- allowance for specific features of hydrodynamics in round and annular sensitive elements;
- adaptability to any dielectric media.

Using intelligent radio frequency sensors, one can determine different parameters of cryogens: <u>in the two-phase region</u> they are the void fraction φ, the quality x, and φ- and x-dependent mean-volume and mean-flow-rate thermodynamic characteristics - enthalpy, density, entropy, etc.; <u>in the single-phase region</u> they are the mean-volume thermodynamic quantities - temperature, density, enthalpy, etc., and in two/three-component mixtures they are concentrations of components. Combining these sensors with orifice plates, turbines, pulsed heat sources, or using them in pairs, one can measure flow rates of both two-phase and single-phase media.

It is reasonable to use intelligent *RF* sensors for diagnostics of cryostabilization systems in superconducting devices, for fast determination of the liquefaction capacity and vapour-liquid expander efficiency, in cryogenic propellant filling systems, in automatic regulation systems of cryogenic installations, for science research.

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REFERENCES

1. E. H. Higman, R. Fell, A. Aiaya, <u>J. Meas.</u> and <u>Contr.</u> 19:47 (1986).
2. A. I. Alexeyev, Yu. P. Filippov, I. S. Mamedov, Flow Pattern of Two-Phase Helium in Horizontal Channels, <u>Cryogenics</u> 31:330 (1991)
3. G. Brianti et al, Chapter 6, Cryogenics, in: "Design Study of the Large Hadron Collider (LHC)," CERN/AC/DI/FA/90-06 (1990), p. 109.
4. V. A. Viktorov, B. V Lunkin, A. S. Sovlukov, RF-Measurements of Technologic Process Parameters,Energoatomizdat, Moscow (1989) (in Russian).
5. S. M. Huang, A. B. Plaskowski, C. G. Xie, M. S. Beck, <u>J. Phys. E.: Sci. Instrum.</u> 3:173 (1989).
6. V. V. Danilov, Yu. P. Filippov, I. S. Mamedov, in: "Advances in Cryogenic Engineering," Vol. 35, Plenum Press, New York (1990), p. 745.

7. "Encyclopedia of Fluid Mechanics," Vol. 3, Gas-Liquid Flow, Ed. N. P. Cheremisinoff, Gulf Publishing Company Book Division, Houston (1985)

8. D. Chisholm, in: "Proc. 13th Intl.Conf. Inst. Rerfig. Congr.," 2:781 (1980).

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Мониторинг Потоков криоагентов:
реализация высокочастотного метода

В работе представлены датчики, контроллеры и методики, применяемые при измерении таких характеристик двухфазных и однофазных потоков криоагентов, как средняя температура T, средняя плотность ρ, истинное объемное паросодержание ϕ, расходное массовое паросодержание x, расход G. Для достижения высокой точности использован высокочастотный метод. При создании чувствительных элементов датчиков учтены гидродинамические особенности течений в каналах круглого и кольцевого поперечных сечений. Описаны интеллектуальные контроллеры двух модификаций: модуль КАМАК и автономный прибор с интерфейсом RS-232. Рассмотрено применение ВЧ датчиков для быстрого определения эффективности парожидкостных детандеров, управления дроссельными устройствами ожижителей и т.д.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1991

Filippov Yu.P. et al. E8-91-366

Monitoring of Cryogenic Flows:
Realization of the Radio Frequency Method

The report presents the sensors, instruments, and methodology to control such characteristics of single-phase and two-phase flows as average temperature T, mean density ρ, void fraction ϕ, quality x, flow rate G. Radio frequency method is used to achieve a high accuracy. The hydrodynamics features specific to channels of round and annular cross-sections are taken into account while working out each type of the sensor. Intelligent controllers of two modifications: a CAMAC module and an independent device equipped with the RS-232 interface are described. Application to fast determination of vapour-liquid expander efficiency, helium liquefaction capacity, etc. is demonstrated.

The investigation has been performed at the Particle Physics Laboratory, JINR.

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