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Abstract

This report is a description of the design and construction of FORTE (Forepumps Test Facility) which has been built in order to enable testing of the pumping speeds of prototypical mechanical forepumps connected in series, as proposed for the ITER forepump system. Three NORMETEX pumps (1300, 600, 60 m^3/h) and one METAL BELLOWS pump (6m^3/h) have been integrated into the test bench.

Measurements of the pumping characteristics were performed, both with the single pumps and with trains of series connected pumps, using the gases N_2, H_2, D_2, He as well as ITER typical gas mixture. The results of the tests are presented.

Tests von trockenen mechanischen Vorpumpen für das ITER-Vakuum-Pumpsystem

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Kurzfassung

Für die Absaugung des Plasma-Abgases und die Vakuumerzeugung in der Plasmakammer der ITER-Fusionsmaschine werden zwei potentielle technische Alternativen untersucht. Zum einen sind das Turbomolekularpumpen mit nachgeschalteten Vorpumpen und zum anderen Kryosorptions- und -kondensationspumpen mit entsprechenden nachgeschalteten Regenerationsaggregaten.

Das Forschungszentrum Karlsruhe GmbH führt im Rahmen des Fusionstechnologie-Programmes der europäischen Gemeinschaft Untersuchungen für die beiden technischen Alternativen durch.

Für das ITER-Abgas-Pumpsystem sind ölfreie mechanische Vorpumpen der Fa. NORMETEX, Frankreich vorgesehen. Bei diesem Pumpentyp handelt es sich um eine in der Pumpzone völlig trockene, d.h. ölfreie Spiralverdrängerpumpe. Desweiteren soll eine Faltenbalgpumpe der Fa. METAL BELLOWS, USA zum Absaugen des Tritiuminventares aus dem ITER-Plasmaexhaust den NORMETEX-Verdichtern nachgeschaltet werden.

Für die Auslegung des ITER-Pumpsystems ist die genaue Kenntnis der Pumpcharakteristik dieser Pumpen in Reihenschaltung erforderlich.

Zur Durchführung der Tests wurde die Versuchsanlage FORTE (Forepumps Testing) installiert. Es wurden zusammen 70 Versuche mit Einzelpumpen und Pumpenkombinationen mit den Gasen H_2, D_2, N_2, He und einem ITER-relevanten Gasgemisch bei den jeweiligen Gegendrücken von 600 und 1200 mbar durchgeführt.

In diesem Bericht werden sowohl die Versuchsanordnung als auch der Versuchsbetrieb beschrieben und die Testergebnisse diskutiert.

Im Gegensatz zu den Einzelpumpen zeigten die Pumpenkombinationen in Reihenschaltung ein besseres Saugvermögen für leichte Gase als für Stickstoff bei Saugdrücken <1 mbar und einem Gegendruck von 600 mbar mit zwei oder mehreren Pumpen bzw. von 1200 mbar mit 4 Pumpen.

Mit den Versuchen konnte demonstriert werden, daß für das Pumpen von Plasma-Abgas von Tokamaks im Saugdruckbereich $>5 \times 10^{-4}$ mbar Spiralverdränger- und Balg-Pumpen geeignet sind.

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1. Introduction

Two types of pump are needed to exhaust the torus of the ITER fusion machine, namely oil-free mechanical pumps (turbomolecular pumps with forepumps connected downstream) and cryopumps (cryosorption and cryocondensation pumps with their downstream connected regeneration units).

Under the EC technology programme KfK is performing investigations of both types of pump. This report deals with mechanical pumps.

Precise knowledge of the pumping characteristic of these pumps, operated either individually or in series, is required in the design of the ITER pumping system.

2. The task

It is envisaged to operate the ITER exhaust pumping system with oil-free mechanical forepumps, both for operation with turbomolecular pumps (pump-down, conditioning) and possibly for regeneration of cryosorption pumps (burn + dwell modes). These modes of operation call for inlet pressures on the order of $5x10^{-4}$ - 10 mbar.

The tests performed at KfK with dry (oil-free) mechanical pumps are geared to optimising the forepump station with a view to ITER. The task consists in testing in series operation the largest dry pumps presently offered on the market with the objective of optimising the configuration of the pump station for operation with ITER typical gas mixtures. Besides, it will be demonstrated that the ITER operating conditions of the exhaust system can be met with the dry mechanical pumps.

The largest dry mechanical forepumps are built by NORMETEX, France. These are positive displacement scroll pumps whose process gas chambers are completely free of oil. The walls of the gas chambers consist exclusively of metal materials without any plastic seals. Three large positive displacement scroll pumps have been installed in the FORTE test facility. METAL BELLOWS, USA, is a supplier of dry positive displacement bellows pumps with, however, a much smaller pumping speed compared to the NORMETEX pumps. The largest bellows pump available has been integrated into the FORTE test facility.

2.1 Optimisation of forepumps

The FORTE test facility has been conceived for measurement of pumping characteristics of prototypes of mechanical forepumps as proposed for the NET / ITER forepump station. The system consists of three NORMETEX pumps (1300, 600, 60 m^3/h) and one METAL BELLOWS pump (6m^3/h). A turbomolecular/molecular drag pump (with magnetic bearings, pumping speed $s > 1000$ l/s) will be integrated into the test set-up later.

2.2 Test matrix

In the tests performed with the FORTE test facility the pump characteristics were used of a test matrix jointly defined with the ITER home team (Table 1) for the gases H_2, D_2, N_2, He and the ITER gas mixture M7 (Table 2) at the respective outlet pressures of 600 and 1200 mbar, both with single pumps and the pump trains NORMETEX-1300+600, NORMETEX-1300+600+60, and NORMETEX-1300+600 +60+METAL BELLOWS-6. 70 tests were necessary. The numbers of the tests can be taken from Table 3.

3. Description of the test facility

3.1 Test facility

To determine the pumping characteristics at the outlet pressures specified in the test matrix (600, 1200 mbar), the test facility (Figure 1) is operated as a closed loop.

All pipe connections >DN16 are made with copper sealed CF-flanges, all connections <DN16 with Cajon-screws.

Media/vacuum contacting parts and components are made from stainless steel. Gate valve and valve seats are Viton sealed. The pipework diameters are DN 63; at the two large positive displacement scroll pumps DN 100 (pressure side) and DN 250 (suction side).

The entire loop inclusive of all pumps has a total volume $V \sim 1.3$ m^3.

The main components of the loop are represented in a simplified block diagram (Figure 2). It shows that the facility consists above all of the closed loop with the three NORMETEX pumps and a METAL BELLOWS pump integrated, the gas flow measuring and metering system, the vacuum station for evacuation of the system, a gas inlet device, and a gas outlet for evacuating the entire loop.

The PNEUROP measuring domes, all the vacuum gate valves and valves, respectively, all safety systems (safety valve, burst disks), a nitrogen flooding system, the coolant water loop, the switching cabinets for process and pump control inclusive of a mimic diagram and the measuring values recording system are not represented in the figure.

3.1.1 Pumps

Two types of pump were tested in the FORTE test facility which operate according to different pump concepts. The units manufactured by NORMETEX, Pont Audemer, France, are so-called positive displacement scroll pumps (Figure 3); the unit supplied by METAL BELLOWS, Sharon, Ma., USA, is a positive displacement double bellows pump with valve seals (Figure 4). The specific principles of design underlying the two concepts guarantee a pumping area completely free of hydrocarbons, which means free of lubricants.

In the **NORMETEX** pumps an eccentrically driven spiral with three windings moves relative to a stationary spiral with $2\frac{1}{2}$ windings without contacting it so that an orbital path is generated. The gap between the two spirals and the compression volumes of the pumps - the two parameters differ depending on the pump size - are characteristic of the pumping speed of the units.

These are the positive displacement scroll pumps used in the FORTE loop:

NORMETEX 1300 m^3/h, duration of test operation t ~ 213 hours (pump Pu1).

NORMETEX 600 m^3/h, duration of test operation t ~ 180 hours (pump Pu2).

NORMETEX 60 m^3/h, duration of test operation t ~ 111 hours (pump Pu3).

After completion of this testing phase, the accumulated running time of the pumps will be (in the order above) 16735, 17642 and 7955 hours.

The **gap widths** between spirals (axial, radial), according to information received from the manufacturer, are 0.17 to 0.20 mm for NORMETEX 1300 m^3/h, 0.15 to 0.17 mm for NORMETEX 600 m^3/h, and 0.09 to 0.10 mm for NORMETEX 60 m^3/h.

The three NORMETEX pumps were operated in a UF_6-loop until 1989. In 1989 pump Pu1, following a defect at the spirals, was partially disassembled and decontaminated at KfK and repaired in the manufacturer's workshop, whereas overhaul and maintenance work on the pumps Pu2 and Pu3 was done on the KfK premises by staff of the manufacturer in 1991. During subsequent trial operation pump Pu1 attained an end pressure of 9×10^{-1} mbar, for air to atmosphere at zero gas flow; Pu2 attained 3×10^{-2} mbar and Pu3 attained 1.8 mbar.

In the **METAL BELLOWS** pump (Pu4) flexible double bellows made of stainless steel and welded to an actuating connecting rod are the basic concept of the mode of operation. The pump chamber in this version is sealed by valve laminated springs (made of stainless steel). In the FORTE test facility a duplex pump in series connection, i.e. including two pump units, is used. This type of pump attains its maximum of throughput at the pressure differential $\Delta p = 0$.

3.1.2 Measuring domes

In order to obtain reproducible pressure measurements for various gas flows, the measuring domes were made to the PNEUROP standard. As they were operated with H_2 (see Chapter 3.5), the domes had to be designed as pressure vessels for a service overpressure $p_B = 12$ bar. The vessels were subjected to both preliminary inspection and final inspection and, in addition, pressure testing by the German Technical Inspectorate (TÜV).

The volume of each dome is $V_M = 0.37$ m^3 and the inner surface is $F_M = 3$ m^2.

3.1.3 Valves and gate valves

All valves and gate valves installed in the test loop are bellows sealed towards the outside. The fittings installed on the pressure side have been designed to withstand an inner pressure $P_d = 3$ bar, the fittings on the suction side for an inner pressure $p_s = 2$ bar, both absolute values. The selected makes are VAT (gate valves, valves) BALZERS (control valves) and NUPRO (isolating valves for the gas metering system).

3.1.4 Gas metering system

The gas metering system consists of five flowmeters for gas flow rates up to 3333 mbarl/s, mounted in a stainless steel casing kept at room temperature, and of an additional instrument for measurement of higher flow rates (see chapter 3.2.1). The gas is supplied into the loop from gas cylinders kept outside the test building in a cylinder store. The pressure of gas supply into the test system is $p_s < 1.5$ bar.

3.1.5 Evacuation unit

Prior to each test the loop is evacuated to an end vacuum $p_{ev} < 1 \times 10^{-5}$ mbar. A turbomolecular pump station (PFEIFFER, type TSU 510) with a helium pumping speed $S_{He} = 570$ l/s is used.

3.1.6 Nitrogen flooding system

To avoid that an inflammable oxyhydrogen mixture is produced in the event of air ingress on the suction side of the NORMETEX pumps, with the risk of explosion associated with the operation with hydrogen, the pump casings are continuously flooded with nitrogen at a slight overpressure $p_o < 10$ mbar which is indicated in a differential pressure gauge mounted on the casings. Also the flooding valve of the turbomolecular pump Pu5 (Chapter 3.1.5) is supplied N_2 for the reason indicated, when the flooding system is switched off.

Moreover, after each test involving H_2 and prior to evacuation of the loop, the process gas is forced out of the pipework using nitrogen.

3.1.7 Coolant water loop

The 15 kW (~ 30% of the nominal power) heat output produced by the driving motors of the tested NORMETEX pumps is removed via a controlled coolant water system by a heat exchanger placed in the oil bath of the pumps in such a manner that both the oil temperature lies in a selectable range of operation (80°C at the maximum) and the thermal equilibrium of the pumps is maintained during operation. The rate of coolant-water supply needed for each pump is 1.25 m^3/h. The coolant-water system is supplied from the KfK fresh water system (service pressure 4 bar, water inlet temperature >10°C; water outlet temperature <30°C). An authorization had to be obtained from the competent supervisory authority for discharge of the coolant water into the KfK storm water system.

3.1.8 Aerosol filters

Given the α-activity in the interior of the pumps (<5.0 Bq/cm^2), as outlined in Chapter 3.1.1, it had be assumed that during exhaust of the gases, followed by the evacuation of the loop, contaminated aerosols are released from the NORMETEX pumps. To avoid the release of radioactivity into the atmosphere, a high efficiency exhaust filter conforming to DIN24184 was integrated into the exhaust pipe. This is due to prior exposure of pumps and is not relevant to these tests

3.2 Measuring instruments

3.2.1 Gas flow

Measuring instruments, type MKS 1259 C, are used to control and measure, respectively, the gas flows in the ranges of measurement 0 to 0.16, 0 to 1.6, 0 to 16.6, 0 to 166, and 0 to 3333 mbar l/s. The first four mass flowmeters are instruments with control features, whereas the latter instrument is only a measuring instrument. The MKS mass flowmeters operate on the thermodynamics principle of measurement and are independent of variations in pressure and temperature. The nominal value, zero point adjustment, nature of gas or correction factor for gas mixtures are set at the four-channel instrument (type MKS 147B).

For higher gas flow rates, up to 38750 mbar l/s, a measuring instrument of ENDRESS + HAUSER, type SWINGWIRL II DV 631, is used. The principle of measurement is the phenomenon of Kármán's vortex path. A delta-shaped baffle barrier is exposed to flow on its front side. Periodically alternating vortexes are generated on the two sides of the baffle barrier which get detached by the flow. The frequency of vortex detachment is proportional to the mean flow velocity and volume flow rate, respectively, above the Reynolds number 3800. Within the specified range of measurement, the measurements made with this instrument are independent of the density and conductivity of the gas. The pressure and temperature are measured and processed in the flow processor.

3.2.2 Pressure

The inlet pressure is measured on the suction side in the PNEUROP domes preceding pumps Pu1 and Pu2 and in the suction pipes just in front of the gas inlet nozzle in pumps Pu3 and Pu4.

Two operating and two precision pressure measuring instruments each have been installed at the domes which cover the entire range of inlet pressures of $10^{-7} < p < 10^{3}$ mbar. The following vacuometers are used: PENNING (cold cathode ionisation gauge, supplied by EDWARDS, type CP 25K, 10^{-7} to 10^{-1} mbar, calibrated for nitrogen), PIRANI (thermal conductivity gauge, supplied by EDWARDS, type PRH 10K, 10^{-3} to 10^{2} mbar, calibrated for nitrogen), and BARATRON (capacitance diaphragm gauge, supplied by MKS, type 390 HA, 10^{-4} to 1 mbar and 10^{-1} and 10^{3} mbar (for any gas used).

Moreover, two BARATRON instruments (MKS, type 390 HA, $1x10^{-3}$ to $1x10^{-1}$ mbar, 10 to 10^{3} mbar) have been mounted between pumps Pu2 and Pu3 and between Pu3 and Pu4 one BARATRON instrument (MKS, type 390 HA, 10 to 10^{3} mbar) as well as one piezo-resistive pressure transducer (WALLACE + THIERNAN, type DPM 35A, 1 to 2 x 10^{3} mbar). One of the latter pressure measuring instruments is installed in addition on the pressure side, i.e. downstream of Pu3 and Pu4, respectively.

3.2.3 Temperature

One temperature measuring point is assigned to each pressure measuring point. Pt 100-sensors are used. They have the following type designations (depending on the range of measurement 50/100/200°C): 30500A1 / 31000A1 / 32000A1 (supplied by KNICK). Additional measuring sensors of the same type allow the temperatures in the oil baths of pumps Pu1, Pu2 and Pu3 to be recorded.

3.3. Control

3.3.1 Instrumentation

The **gas flow** is recorded by six flowmeters for different ranges of measurement and based on different measuring principles (Chapter 3.2.1). Each flowmeter is equipped with a control valve so that the desired gas flow rate can be exactly set and maintained. The respective flow rate is controlled and indicated by an instrument with microprocessor-controlled data handling. The ranges of measurement and the types of gas are input as a menu and the flow rates are corrected automatically, taking into account the gas factors. The gas flow rate is displayed as a digital signal; the analogue output signal is 0 to 5 V.

The **inlet pressures** of pumps Pu1 and Pu2 are measured in the preceding PNEUROP domes, the inlet pressures of pumps Pu3 and Pu4 in the pipes just in front of the suction port. The pressure measuring instruments are equipped with digital display fields. The instruments deliver analogue voltage signals of 0 to 10 V for data processing.

The **gas temperature** is recorded by platinum resistors in four-wire technique and converted into a digital display signal and an analogue voltage output of 0 to 10 V.

Likewise,the **oil bath temperatures** in the NORMETEX pumps are measured with platinum resistors and used for automatic control of the coolant circuit (Chapter 3.1.7) (initial signal: 0 to 20 mA).

The measuring domes are equipped with heater jackets, temperature sensors and controls so that specified **baking temperatures** and times can be specifically set (during evacuation).

3.3.2 Operating equipment

Each NORMETEX pump has its own supply and control cabinet. All the other plant components (heaters, gate valves, valves), the flowmeter measuring points, pressure measuring points and temperature measuring points are controlled via a mimic diagram in a flow chart representation. Optical intermittent signals and acoustic alarms give indications of malfunctions or disturbances. The whole facility can be operated and monitored both automatically and manually by a freely programmable control system.

3.4 Recording of measured values

3.4.1 Requirements on the system

The software used stores the measured data, processes them on-line and displays the results both as graphics or in an analogue representation. With the IMPs (Isolated Measurement Pods) used, the accuracy is attained by a C-program integrated in the user program.

3.4.2 Requirements on the software

The recorded measuring values are stored and digitised. Quick representation of the measured values is possible at any moment, either on-line or as print-outs.

3.4.3 Decentral recording of measured values

If necessary, the system can be extended to comprise up to 200 channels. The program allows both the input of data and monitor displays or recording of measured values. Related to the respective voltage range, the accuracy of resolution is 16 bits. By use of the so-called Solartron S-net the electronic system can be directly connected to the transducers.

3.4.4 Data processing system

Considering a potential future expansion of the system, e.g. additional networking, new tasks, a DEC-station was used with an 80386-processor and a 32-bit bus. Connection to further, already existing DEC-stations is feasible. The software chosen for recording and evaluation of the data generated is ASYST, which is capable of communicating with other codes (e.g. FORTRAN, C, DOS).

The raw data are stored first without, then also together with the parameters used for calibration.

3.4.5 Evaluation software

The following displays and print-outs, respectively, can be made:

- flow rate, inlet pressure, gas temperature, temperature of the oil bath;
- pumping speed for various gases and for a gas mixture at various outlet pressures versus inlet pressures.

3.5 Safety aspects and safety devices

Operation involving H_2 might cause problems if, due to a leak, air enters the circuit on the suction side and together with the process gas makes up an inflammable oxyhydrogen mixture. Even mechanically moved parts contacting each other might be a source of ignition. This is the reason why the application of transducers has been dispensed with which, on account of their characteristic and mode of operation, constitute sources of ignition.

Moreover, it has been ensured that hydrogen can be admitted to the system only if a slight negative pressure (<200 mbar) prevails there. This is detected by two series-connected pressure switches which, in turn, can open the gas inlet valve only if actuated simultaneously.

To avoid inadmissible overpressure during operation in the system, a reversible burst disk, 2 bar opening pressure, was installed on the suction side and one on the pressure side, opening pressure 3 bar. As a protection of the METAL BELLOWS pump another reversible burst disk, 3 bar opening pressure, has been installed upstream of a safety valve in a blowdown pipe of the bypass.

Another measure geared to prevent air from entering the NORMETEX pumps on the suction side consists in flooding with nitrogen the pump casing and the flooding valve of the evacuation unit (Chapter 3.1.6).

A check valve was mounted at the end of the blowdown pipe to prevent air backflow from the ambient atmosphere. Besides, a permanent fireproof protective flap was installed at the mouth of the pipe as a measure of precaution.

4. Test operation

Before a test is started, the facility is evacuated to an end pressure $<1 \times 10^{-5}$ mbar. Then, the respective oil circulating pump and the oil heating system of the pump and pump train to be tested are switched on. When the specified oil temperature has been attained which must not be below the corresponding gas temperature (5-6°C tolerance), the pumps can be put in service. While pump Pu1 must be started manually after the clearance message, pumps Pu2 and Pu3 are connected automatically.

Then the loop can be filled manually on the pressure side (for pump trains downstream of the last pump) with the selected process gas until the desired outlet pressure is attained.

The first value determined in the test is the end pressure at the gas flow rate $q = 0$. For this, the pump and pump train, respectively, are isolated by gate valves on the suction side and the values measured are recorded. Then the test proper can be started: Beginning with the lowest up to the highest gas flow, the gas flow rates are increased stepwise and the corresponding inlet pressure values are recorded after the state of equilibrium has been attained. This is done both via the measured-data recording system and in situ by manual recording.

5. Results and discussion

5.1 Tests with single pumps

In the single-pump tests the best values of pumping speed were measured for the three positive displacement scroll pumps (Tables 4 and 5). NORMETEX-1300 attains for nitrogen a maximum of 252 l/s at an outlet pressure of 600 mbar and a maximum of 220 l/s at 1200 mbar. The corresponding values for hydrogen, the most badly pumped gas, are 71 l/s (600 mbar) and 43 l/s (1200 mbar), respectively. The plots for the other gases lie between those for N_2 and H_2; those for D_2 and M7 are nearly identical (Figures 5 and 6).

The NORMETEX-600 and NORMETEX 60 pumps exhibit a similar course of the pumping speeds (Figures 7 to 19).

By reduction of the outlet pressure from 1200 to 600 mbar increases in the pumping speed by the factor of 1.1 - 2.5 for nitrogen and by the factor of 1.4 - 1.7 for hydrogen were achieved. The influence exerted on the compression ratio by reduction of the outlet pressure from 1200 to 600 mbar is even more pronounced: the measured increase is by a factor of 2 - 142 for N_2 and 2.9 to 24.4 for H_2, respectively.

The pumping behaviour of the METAL BELLOWS pump differs from that of the NORMETEX pumps on account of the differences in design and function of that pump. The pump does not exhibit noticeable differences in pumping speed for the various gases: nitrogen is pumped slightly worse compared with the other gases, and for hydrogen a slightly higher maximum of the pumping speed is measured compared with the other gases. The reduction of outlet pressure from 1200 to 600 mbar does not exert a remarkable influence on the pumping speed or compression ratio: for hydrogen the pumping speed is diminished slightly, by approx. 6% (Figures. 11 and 12).

The best end pressure at zero gas flow and 1200 mbar outlet pressure, i.e. $p = 3.5 \times 10^{-2}$ mbar for N_2, was measured with the NORMETEX-600 pump, the worst, i.e. $p = 7.9 \times 10^{2}$ mbar for H_2, with the NORMETEX-60 pump. At 600 mbar outlet pressure the best end pressure measured has been $p = 9 \times 10^{-3}$ mbar for N_2 (NORMETEX-600 pump), the worst, $p = 1.4 \times 10^{2}$ mbar for H_2 (NORMETEX-60 pump). The data for all gases and pumps, respectively, have been entered in Tables 4 and 5.

The differences in the end pressures and compression ratios measured with the positive displacement scroll pumps under unchanged conditions of operation can be explained by the differences in design. The gaps between the spiral shaped rotors and stators of the pumps set a limit on the end pressure because of the backflow of compressed gas to the suction side in the range of molecular flow. In order to achieve better end pressures, larger compression volumes and hence less gas leak flows would be required. The smallest NORMETEX pump tested

(60 m^3/h) has an adverse volume to leak flow ratio which is reflected by the comparatively high end pressure. The largest NORMETEX pump (1300 m^3/h), by contrast, has a favourable volume to leak flow ratio, albeit a larger dead volume. For this reason, relatively high end pressures were measured for this pump.

The test results obtained with the single pumps (NORMETEX) are comparable with the results of earlier tests performed with smaller pump units [1] which means that, compared with nitrogen, the pumping speed measured for the light gases was worse.

5.2 Tests with two series-connected pumps

In dual-pump series connected operation (NORMETEX-1300 + 600) the maximum of the pumping speed plots is shifted towards lower inlet pressures (Figures 13 and 14). Compared with the results obtained in the single-pump mode, the pumping speed increases by the factor of 1.25 (1.09) for N_2 at 1200 (600) mbar outlet pressure, and by the factor of 1.49 (3.8) for H_2 (Tables 6 and 7). Moreover, the end pressure for N_2 is also improved to 1.1×10^{-5} (6.0×10^{-6}) mbar and for H_2 to 1.1 (1.1×10^{-3}) mbar. These measurements are supplemented by quite a remarkable increase in the compression ratios: for N_2 to 1.1×10^8 (1.0×10^8) and for H_2 to 1.1×10^3 (5.4×10^5).

The most noticeable qualitative difference between the single and dual pump modes of operation is reflected by the change in the pumping speed such that hydrogen in dual pump operation at 600 mbar outlet pressure is pumped better in the range of inlet pressures 10^{-2} - 1 mbar than nitrogen is (Figure 14).

Figs. 15 to 18 show the pumping speed at the inlet of the pumps for N_2 and H_2 at 1200 and 600 mbar exhaust pressure.

5.3 Test with three series-connected pumps

By extension of the pump train (Chapter 5.2) by the third pump (NORMETEX-1300 + 600 + 60) the pumping speed for H_2 is raised to 270 (272) l/s at 1200 (600) mbar outlet pressure, i.e. to the N_2-level. The maximum of pumping speed for nitrogen remains practically unchanged (Figures 19 and 20). Besides, a marked improvement of the end pressure can be noticed for H_2, namely to 3.3×10^{-3} (1.4×10^{-5}) mbar. This gives a compression ratio of 3.3×10^5 (4.3×10^7).

Figs. 21 to 24 show the pumping speed at the inlet of the pumps for N_2 and H_2 at 1200 and 600 mbar exhaust pressure.

5.4 Test with four series-connected pumps

After connection of the fourth pump in series (NORMETEX-1300 + 600 + 60+METAL BELLOWS 6) no substantial changes in the maxima of pumping speeds are observed compared with the results obtained with the pump train in Chapter 5.3 (Figures 25 and 26). For H_2 a slight increase to 275 (273) l/s can be observed. The end pressure continues to drop to 2.0×10^{-5} (8.0×10^{-6}) mbar which implies an improvement of the compression ratio of 6.0×10^{7} (7.5×10^{7}).

Figs. 27 to 30 show the pumping speed at the inlet of the pumps for N_2 and H_2 at 1200 and 600 mbar exhaust pressure.

The relevant data for all test gases and pump trains have been entered in Tables 6 and 7.

These tests allow evidence to be provided that also at the high outlet pressure of 1200 mbar light gases such as H_2, D_2 and the M7-gas mixture are pumped better than nitrogen in the range of inlet pressures < 1 mbar.

The more favourable pumping speed observed for hydrogen compared to that of nitrogen can be explained by the higher conductances of hydrogen in the range of molecular flow. The operation domain of pump trains in comparison to single pumps shifts to lower pressures where the molecular flow dominates.

The test results make obvious that dry mechanical pumps are suited to pump effectively light gases as well as typical Tokamak plasma exhaust mixtures. The optimum range of inlet pressures for application of these pumps as forepumps together with hybrid turbomolecular/drag pumps is between 10^{-1} and 10 mbar where the pumping speed for light gases attains values beyond 200l/s. The lower limit of suction pressures for application of these pumps is $\sim 5.0 \times 10^{-4}$ mbar with a pumping speed for light gases of more than 60 l/s.

5.5 Behaviour of gas and oil temperatures

5.5.1 Gas temperatures

The initial temperature of the gases on the suction side is determined by the ambient temperature. No changes in temperature within the tolerance margin ± 1°C were observed during the tests.

By contrast, a maximum rise in temperature of up to ΔT = 35°C was measured for the single pumps (NORMETEX-600, gas mixture M7, 1200 mbar outlet pressure) and of up to ΔT = 39°C for the train of two pumps (He, 1200 mbar) for all gases, starting at inlet pressures > 10 mbar. For trains of three and four pumps this temperature rise reduced down to values of as little as 2.6°C (gas mixture M7), 1200 mbar outlet pressure) and 1.7°C, respectively (H_2, 1200 mbar).

It has been a remarkable finding for the NORMETEX-1300+600+60 train that the temperature rise downstream of the second pump is more pronounced (ΔT~11°C, H_2, 1200 mbar) than at the end of the pump train.

5.5.2 Oil temperatures

The maximum tolerable oil temperature of the NORMETEX pumps is 80°C. Beyond this limit, which had not been attained during the tests, the compressors are automatically switched off.

The developments of the oil temperatures of the NORMETEX-1300 pump for all test gases at 1200 and 600 mbar outlet pressures are visible from Figures 31 and 32. The maximum temperature and hence the maximum temperature rises were measured for this pump. The smallest increases in temperatures were recorded for the NORMETEX-60 pump (ΔT = 1 to 13°C; 1200 mbar).

For the NORMETEX-1300+600 pump train the maximum oil temperature of T = 65°C (NORMETEX-600) was measured for N_2 at 1200 mbar outlet pressure. The 42.5°C temperature in the oil bath of NORMETEX 1300 was lower by ΔT = 22.5°C. In general, the plots of the oil temperature of the NORMETEX-600 compressors at suction pressures above ~10^{-1} mbar were above those of the NORMETEX -1300 pump (Figure 33).

The same was observed for the train consisting of the three pumps NORMETEX-1300+600+60; the temperatures of the NORMETEX-60 pump ranged between those of the NORMETEX -1300 and 600 pumps. In this case, the maximum temperature T = 52°C was indicated in the oil bath of the NORMETEX-600 pump for H_2 (1200 mbar outlet pressure) (Figure 34). Only in the He-test the rise in temperature in the oil bath of the NORMETEX-60 pump to T = 42°C at the maximum was higher than for the pumps NORMETEX-600 (T = 40°C at the maximum) and 1300 (T = 35°C at the maximum).

The least rise in temperature was measured for the NORMETEX-1300+600 +60+METAL BELLOWS-6 pump train. For M7 at 1200 mbar outlet pressure a maximum temperature T = 46°C was measured in the oil bath of the NORMETEX 600 pump. The oil temperatures of the other two positive displacement scroll pumps remained below the 40°C mark (Figure 35).

6. Conclusions

Dry positive displacement scroll pumps and bellows vacuum pumps were tested individually and in series of up to four units with the gases H_2, D_2, N_2, He and a representative Tokamak plasma exhaust mixture.

With single pumps operated, the best pumping speed for all gases tested, measured for all three scroll pumps, was that for nitrogen (Tables 1, 2). The largest scroll pump attains for N_2 a maximum pumping speed of 252 l/s and for protium of 71 l/s at 600 mbar exhaust pressure. Protium was pumped least effectively and the pumping curves for other gases lie between those of N_2 and H_2. The pumping speeds for D_2 and for the M7 gas mixture are almost identical .

Reduction of the exhaust pressure from 1200 mbar to 600 mbar results for the scroll pumps in a rise in pumping speed by a factor of 1.1 - 2.5 for N_2 and of 1.4 - 1.7 for H_2. The change in exhaust pressure has an even greater influence on the compression ratio of the scroll pumps. With the exhaust pressure reduced from 1200 to 600 mbar, a rise in the compression ratio by the factor 2 - 142 was measured for N_2 and of 2.9 - 24.4 for H_2.

The pump characteristic of the bellows pump differs from that of the scroll pumps due to differences in design: however, for the bellows pump no noticeable differences have been found as regards the pumping speeds of different gases. Helium is pumped marginally worse than the other gases, and for protium a slightly higher maximum pumping speed has been measured as compared to nitrogen. Other than for the scroll pumps in case of reduction from 1200 to 600 mbar, no significant influence has been detected of the exhaust pressure, neither on the pumping speed nor on the compression ratio for the bellows pump. The pumping speed for protium has diminished slightly, i.e. by 6% upon reduction of the exhaust pressure from 1200 to 600 mbar.

Of all single pumps tested the best ultimate pressure at zero delivery of 3.5×10^{-2} mbar was measured for nitrogen with the NORMETEX 600 pump.

The differences in ultimate pressures and compression ratios which had been measured for the scroll pumps with the other operating conditions remaining unchanged can be explained by the differences in design. The gaps between the spiral shaped rotors and stators limit the ultimate pressures due to backflow of compressed gas (NORMETEX 60: 0.09 - 0.10 mm, NORMETEX-600: 0.15 - 0.17 mm), NORMETEX 1300: 0.17 - 0.20 mm). To achieve lower ultimate pressures larger compression volumes and less backflow are needed. The smallest scroll pump tested (NORMETEX 60) has an unfavourable volume/backflow ratio, which results in a relatively high ultimate pressure. The largest scroll pump (NORMETEX 1300) has an advantageous volume/backflow ratio. But it has an enlarged dead volume which results also in a relatively high ultimate pressure.

In the tests involving single pumps the results of earlier tests performed with small units have been confirmed [1]. In other words, the poorest pumping speed has been measured for light gases compared with nitrogen.

After a second pump has been connected in series (NORMETEX 1300+600) the maximum of the pumping speed curves is shifted towards lower pressures. Compared with the single-pump mode of operation, the pumping speed is increased by the factor 1.25 (1.09) for N_2 at 1200 (600) mbar exhaust pressure and by the factor 1.49 (3.80) for H_2. Likewise, the ultimate pressures have been greatly improved: for N_2 to 1.1×10^{-5} (6×10^{-6}) mbar and for H_2 to 1.1 (1.1×10^{-3}) mbar. This has been accompanied by a remarkable increase in the compression ratio: for nitrogen to 1.0×10^{8} (1.1×10^{8}) and for protium to 1.1×10^{3} (5.4×10^{5}).

The major qualitative difference between the single-pump and two-pump modes of operation consists of the change in pumping speed in such a way that at 600 mbar exhaust pressure protium is delivered better than nitrogen in the two-pump mode and in suction pressure range 10^{-2} - 1 mbar

After the third pump had been connected in series (NORMETEX 1300+600+60) the pumping speed for H_2 was raised to 270 (272) l/s, i.e. to N_2 level. The maximum pumping speed for nitrogen remained practically unchanged. Likewise, it has been possible to improve considerably the ultimate pressure of H_2, namely to 3.3×10^{-3} (1.4×10^{-5}) mbar. This corresponds to a compression ratio of 3.6×10^{5} (4.3×10^{7}).

After the fourth pump had been connected in series (NORMETEX 1300 + 600 + 60 + METAL BELLOWS 6) no changes were detected in the maximum pumping speed as compared with different combinations of pumps. However, in that case it was possible to demonstrate also for the high exhaust pressure of 1200 mbar that the light gases H_2, D_2 and the M7 gas mixture are pumped better than nitrogen in the range of suction pressures < 1 mbar.

The observed better pumping of protium compared with nitrogen can be explained by higher conductances for H_2 than for N_2 in the molecular flow regime.

It is evident from the results of these tests that dry mechanical pumps are suited for exhausting light gases and typical Tokamak plasma exhaust mixtures as backing pumps for primary cryopumps or mechanical pumps.

The optimum range of suction pressures for application of these pumps as forepumps of hybrid turbomolecular/molecular drag pumps lies between 10^{-1} and 10 mbar where the pumping speed for light gases attains values in excess of 200 l/s.

The lower limit of suction pressure for application of these pumps occurs at $\sim 5 \times 10^{-4}$ mbar, with the pumping speed for light gases above 60 l/s.

7. Acknowledgements

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8. Reference

[1] U. Berndt, E. Kirste, T. Le, M. Glugla, R.-D. Penzhorn: Performance characteristics of large scroll pumps, Fusion Engineering and Design 18 (1991) 73-77.

9. Tables

10. Figures

Fig. 18 Pumping speed at the inlet of pumps of NORMETEX-1300+600 pump train for H_2 at 600 mbar exhaust pressure.

Fig. 19 Pumping speed of NORMETEX-1300+600+60 pump train for various gases at 1200 mbar exhaust pressure.

Fig. 20 Pumping speed of NORMETEX-1300+600+60 pump train for various gases at 600 mbar exhaust pressure.

Fig. 21 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60 pump train for N_2 at 1200 mbar exhaust pressure.

Fig. 22 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60 pump train for N_2 at 600 mbar exhaust pressure.

Fig. 23 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60 pump train for H_2 at 1200 mbar exhaust pressure.

Fig. 24 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60 pump train for H_2 at 600 mbar exhaust pressure.

Fig. 25 Pumping speed of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for various gases at 1200 mbar exhaust pressure.

Fig. 26 Pumping speed of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for various gases at 600 mbar exhaust pressure.

Fig. 27 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+ METAL BELLOWS-6 pump train for N_2 at 1200 mbar exhaust pressure.

Fig. 28 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+ METAL BELLOWS-6 pump train for N_2 at 600 mbar exhaust pressure.

Fig. 29 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for H_2 at 1200 mbar exhaust pressure.

Fig. 30 Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+ METAL BELLOWS-6 pump train for H_2 at 600 mbar exhaust pressure.

Fig. 31 Oil temperature of NORMETEX-1300 pump for various gases at 1200 mbar exhaust pressure.

Fig. 32 Oil temperature of NORMETEX-1300 pump for various gases at 600 mbar exhaust pressure.

Fig. 33 Oil temperature of NORMETEX-1300+600 pump train for gas mixture M7 at 1200 mbar exhaust pressure.

Fig. 34 Oil temperature of NORMETEX-1300+600+60 pump train for gas H_2 at 1200 mbar exhaust pressure.

Fig. 35 Oil temperature of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for M7 gas mixture at 1200 mbar exhaust pressure.

To be measured: pump performance

Gas	Outlet Pressure	
	600 mbar	1200 mbar
N2	x	x
He	x	x
H2	x	x
D2	x	x
M7 *)	x	x

*) simulated ITER gas mixture

The test matrix is valid for the individual tests of the forepumps 1300, 600, 60 and 6 cbm/h and for the series combinations 1300 + 600, 1300 + 600 + 60 and 1300 + 600 + 60 + 6 cbm/h.

Gas Flow Range: 0.05 - 100000 mbarl/s

Tab.1: FORTE test matrix

Hydrogen	:	99.9999
Deuterium	:	99.8
Helium	:	99.9999
Nitrogen	:	99.996
Gas mixture:		3 He, 1.12 CH_4, 1 H_2, 0.16 CO, 0.16 N_2, 0.16 O_2, 0.08 Ar, 0.08 CO_2, remainder D_2

(all data in vol-%)

Tab.2: Gases used in the FORTE tests

Pump/Pump trains	Exhaust pressure [mbar]	M7 *)	H2	D2	N2	He
Pu1	600	V40	V51	V65	V28	V82
(NORMETEX-1300)	1200	V47	V52	V66	V23/26	V83
Pu2	600	V41	V53	V67	V24	V84
(NORMETEX-600)	1200	V46	V55	V68	V25	V85
Pu3	600	V42	V61	V73	V29	V80
(NORMETEX-60)	1200	V48	V62	V74	V30	V81
Pu4	600	V70	V63	V75	V31	V78
(METAL BELLOWS-6)	1200	V49	V64	V76	V32	V79
Pu1 + Pu2	600	V43	V56	V77	V33	V86
	1200	V45	V54	V69	V34	V87
Pu1 + Pu2 + Pu3	600	V44	V57	V92	V35	V88
	1200	V50	V60	V111	V36	V89
Pu1 + Pu2 + Pu3 + Pu4	600	V71	V58	V109	V37	V90
	1200	V72	V59	V110	V38	V91

*) simulated ITER gas mixture

Tab.3: Synopsis of tests performed

Pump	Max. pumping speed (l/s)					Ultimate pressure (mbar)					Compression ratio (zero flow)				
	H2	D2	N2	M7	He	H2	D2	N2	M7	He	H2	D2	N2	M7	He
NORMETEX 1300	43	51	220	57	74	3,7 x E+2	8,8 x E+1	1,6	3,3 E+1	1,1 x E+1	3,2	1,3 x E+1	7,5 x E+2	3,7 x E+1	1,1 x E+2
NORMETEX 600	41	46	134	47	53	3,5 x E+2	1,9 x E+1	3,5 x E-2	1,2 x E+1	8,0 x E-1	3,4	6,3 x E+1	3,4 x E+4	1,0 x E+2	1,5 x E+3
NORMETEX 60	4,1	4,5	6	4	5	7,9 x E+2	5,7 x E+2	4,2 x E+1	6,5 x E+2	2,8 x E+2	1,5	2,1	1,4 x E+1	1,8	4,3
METAL BELLOWS 6	1,6	1,5	1	1,4	1,5	8,4 x E+1	8,0 x E+1	7,3 x E+1	8,1 x E+1	8,2 x E+1	1,4 x E+1	1,5 x E+1	1,6 x E+1	1,5 x E+1	1,5 x E+1

Tab.4: Pumping data of single pumps for various gases at 1200 mbar exhaust pressure

Pump	Max. pumping speed (l/s)					Ultimate pressure (mbar)					Compression ratio (zero flow)				
	H2	D2	N2	M7	He	H2	D2	N2	M7	He	H2	D2	N2	M7	He
NORMETEX 1300	71	145	252	109	213	1,6 x E+1	3,1	1,3 E-1	2,3	9,5 x E-1	3,8 E+1	1,9 x E+2	4,5 x E+3	2,6 x E+2	6,3 x E+2
NORMETEX 600	59	99	141	106	131	7	4,0 x E-1	9 x E-3	4,0 x E-1	5,5 x E-2	8,3 x E+1	1,5 x E+3	6,7 x E+4	1,5 x E+3	1,0 x E+4
NORMETEX 60	6	6,3	15	6,3	12	1,4 x E+2	2,3 x E+1	2,9 x E-1	1,8 x E+1	7,6 x E-1	4,3	2,6 x E+1	2,0 x E+3	3,3 x E+1	7,9 x E+2
METAL BELLOWS 6	1,5	1,3	1	1,3	1,3	4,4 x E+1	4,5 x E+1	3,6 x E+1	4,5 x E+1	4,5 x E+1	1,3 x E+1	1,3 x E+1	1,6 x E+1	1,3 x E+1	1,3 x E+1

Tab.5: Pumping data of single pumps for various gases at 600 mbar exhaust pressure

Pump trains	Max. pumping speed (l/s)					Ultimate pressure (mbar)					Compression ratio (zero flow)				
	H2	D2	N2	M7	He	H2	D2	N2	M7	He	H2	D2	N2	M7	He
NORMETEX 1300 + 600	64	262	274	261	264	1,1	1,4 x E-3	1,1 x E-5	1,1 x E-3	2,0 x E-4	1,1 x E+3	8,5 x E+5	1,1 x E+8	4,6 x E+5	6,0 x E+6
NORMETEX 1300+600+60	270	274	276	266	274	3,3 x E-3	4,0 x E-4	4,0 x E-6	1,0 x E-4	6,0 x E-6	3,6 x E+5	3,0 x E+6	3,0 x E+8	1,2 x E+7	2,0 x E+8
NORMETEX 1300+600+60+ METAL BELLOWS 6	275	274	262	269	275	2,0 x E-5	3,0 x E-4	2,0 x E-6	3,0 x E-4	7,0 x E-6	6,0 x E+7	4,0 x E+6	6,0 x E+8	4,0 x E+6	1,7 x E+8

Tab.6: Pumping data of pump trains for various gases at 1200 mbar exhaust pressure

Pump trains	Max. pumping speed (l/s)					Ultimate pressure (mbar)					Compression ratio (zero flow)				
	H2	D2	N2	M7	He	H2	D2	N2	M7	He	H2	D2	N2	M7	He
NORMETEX 1300 + 600	270	270	275	263	276	1,1 x E-3	2,0 x E-4	6,0 x E-6	6,0 x E-4	2,0 x E-6	5,4 x E+5	3,0 x E+6	1,0 x E+8	1,0 x E+6	3,0 x E+8
NORMETEX 1300+600+60	272	267	276	265	277	1,4 x E-5	3,0 x E-6	4,0 x E-6	1,3 x E-5	1,0 x E-6	4,3 x E+7	2,0 x E+8	1,5 x E+8	4,6 x E+7	6,0 x E+8
NORMETEX 1300+600+60+ METAL BELLOWS 6	273	274	260	269	269	8,0 x E-6	5 x E-6	9,0 x E-6	4,0 x E-6	1,0 x E-6	7,5 x E+7	1,2 x E+5	6,6 x E+7	1,5 x E+8	6,0 x E+8

Tab.7: Pumping data of pump trains for various gases at 600 mbar exhaust pressure

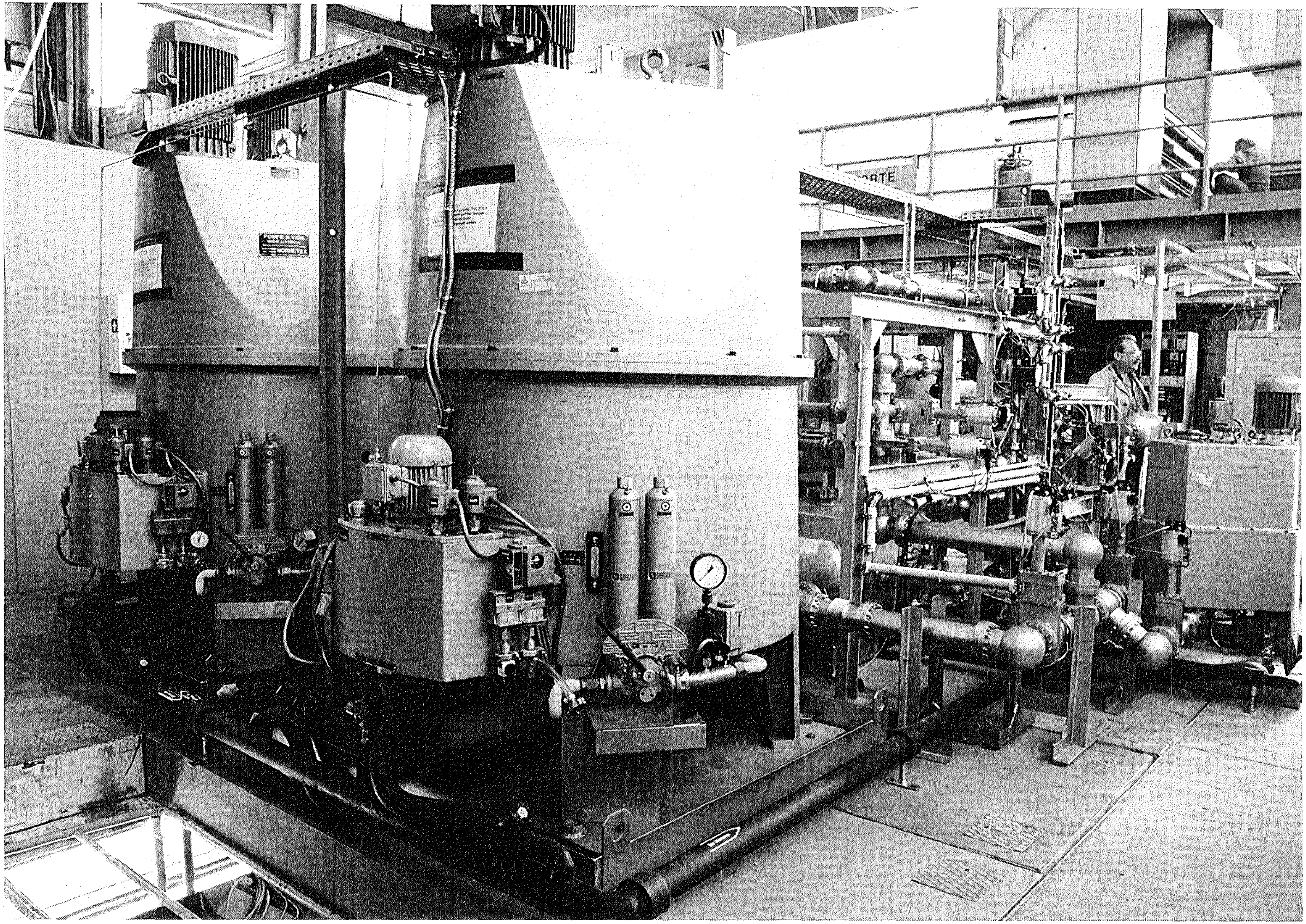


Fig.1: FORTE test facility

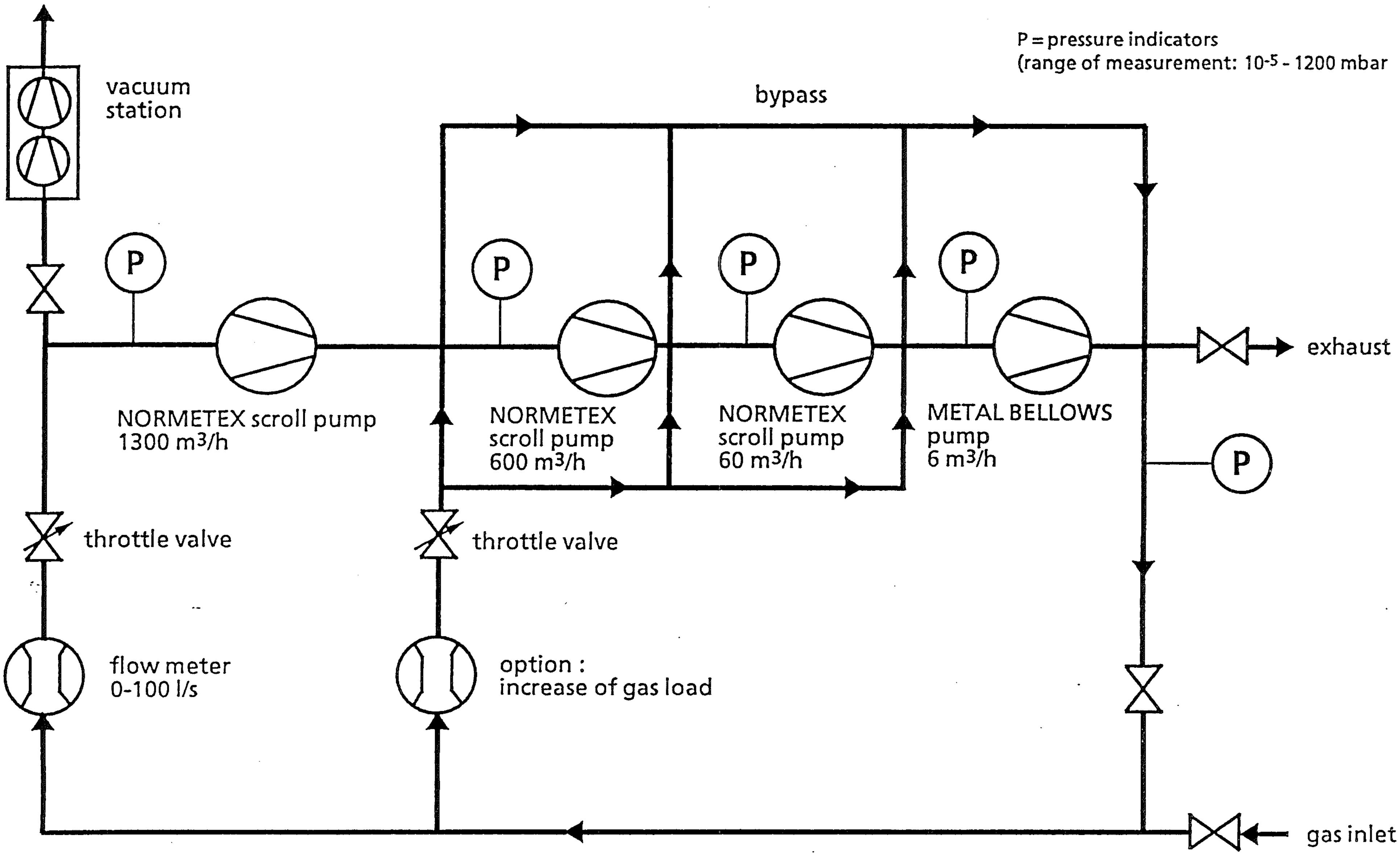


Fig.2: FORTE block diagram

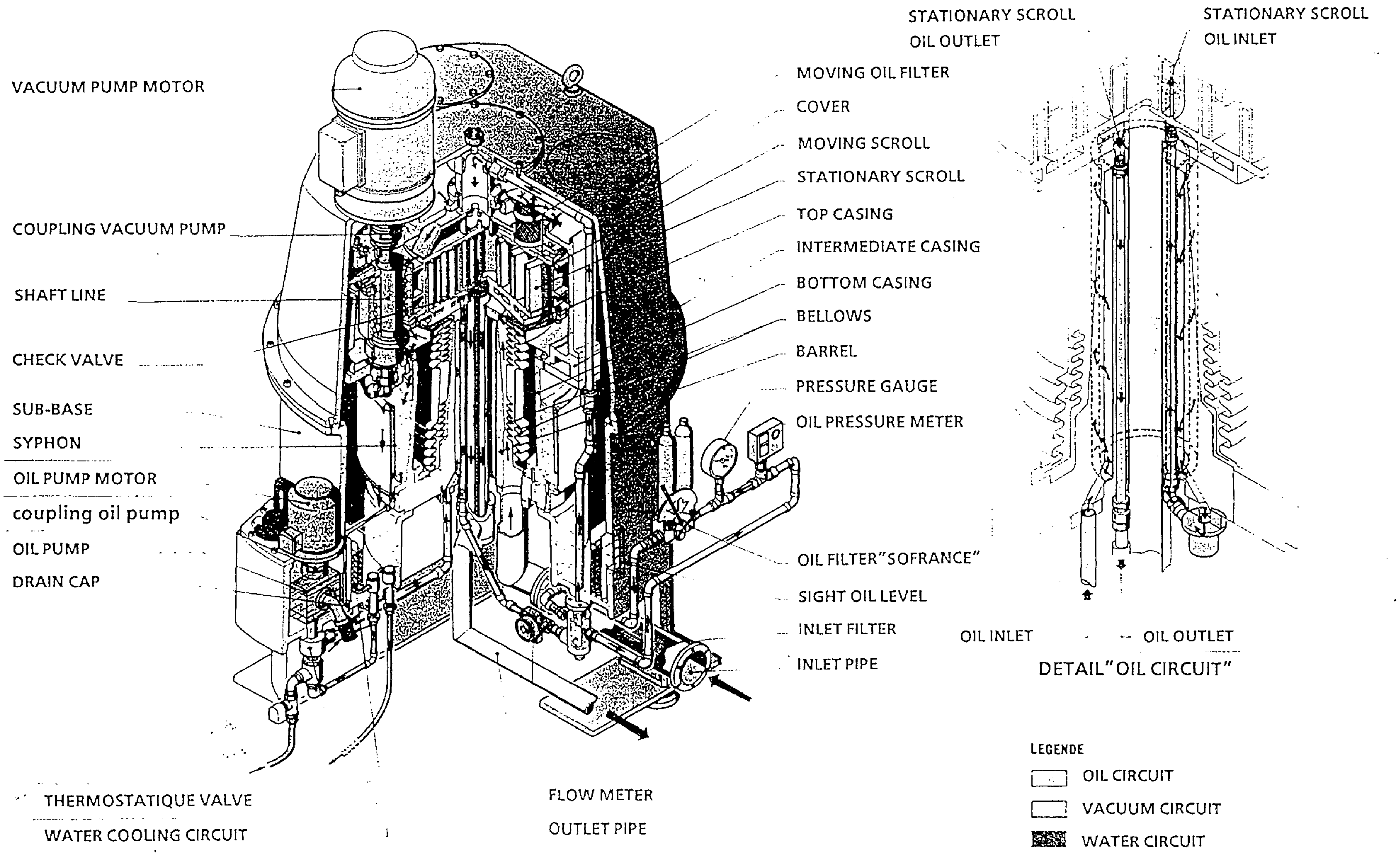
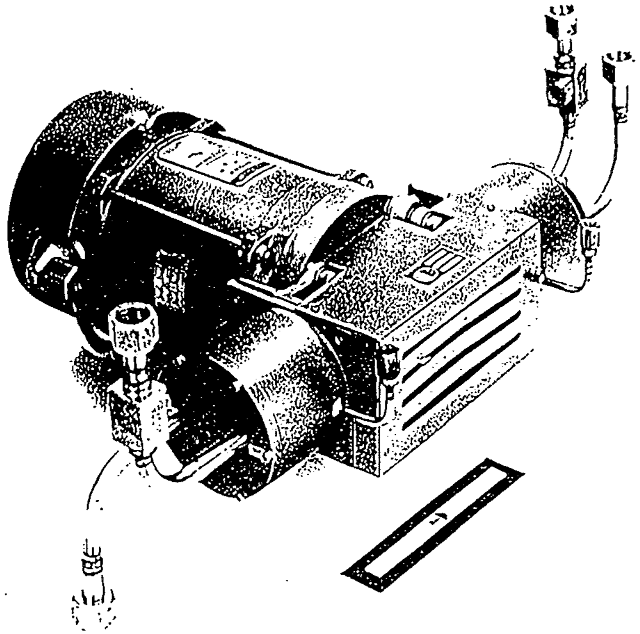
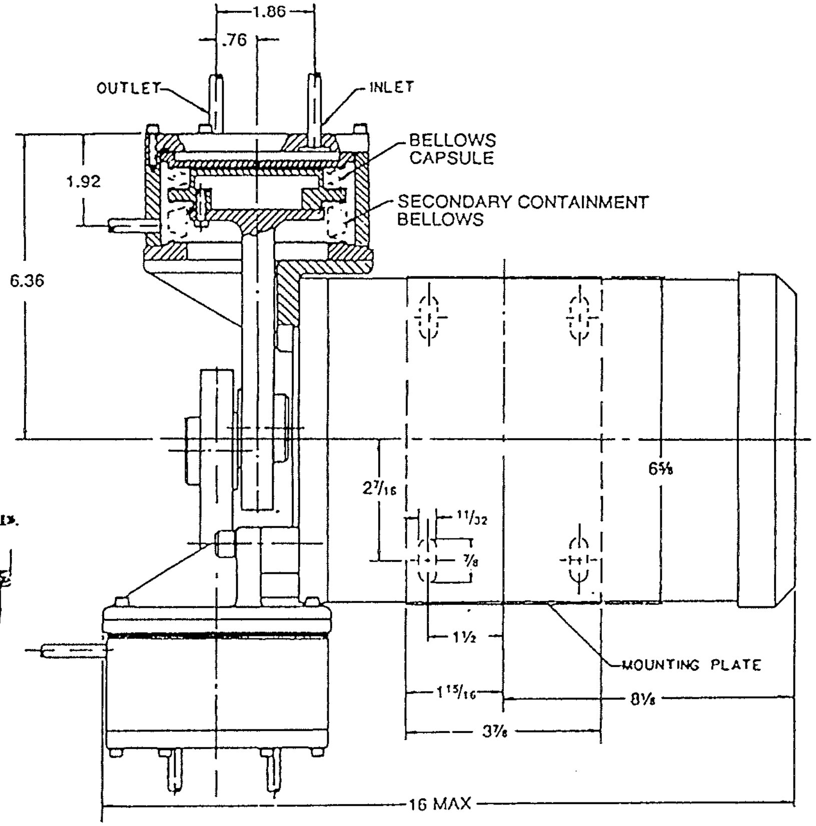


Fig.3: NORMETEX pump





MB-601 DUPLEX MODEL DOUBLE CONTAINMENT PUMP
Schematic shows top view of pump. Tubes from front of pump lead from double containment chambers formed by secondary containment bellows. Pressure sensors attached to tubes will shut pump down safely in event of pump or secondary bellows failure.

Fig.4: METAL BELLOWS pump

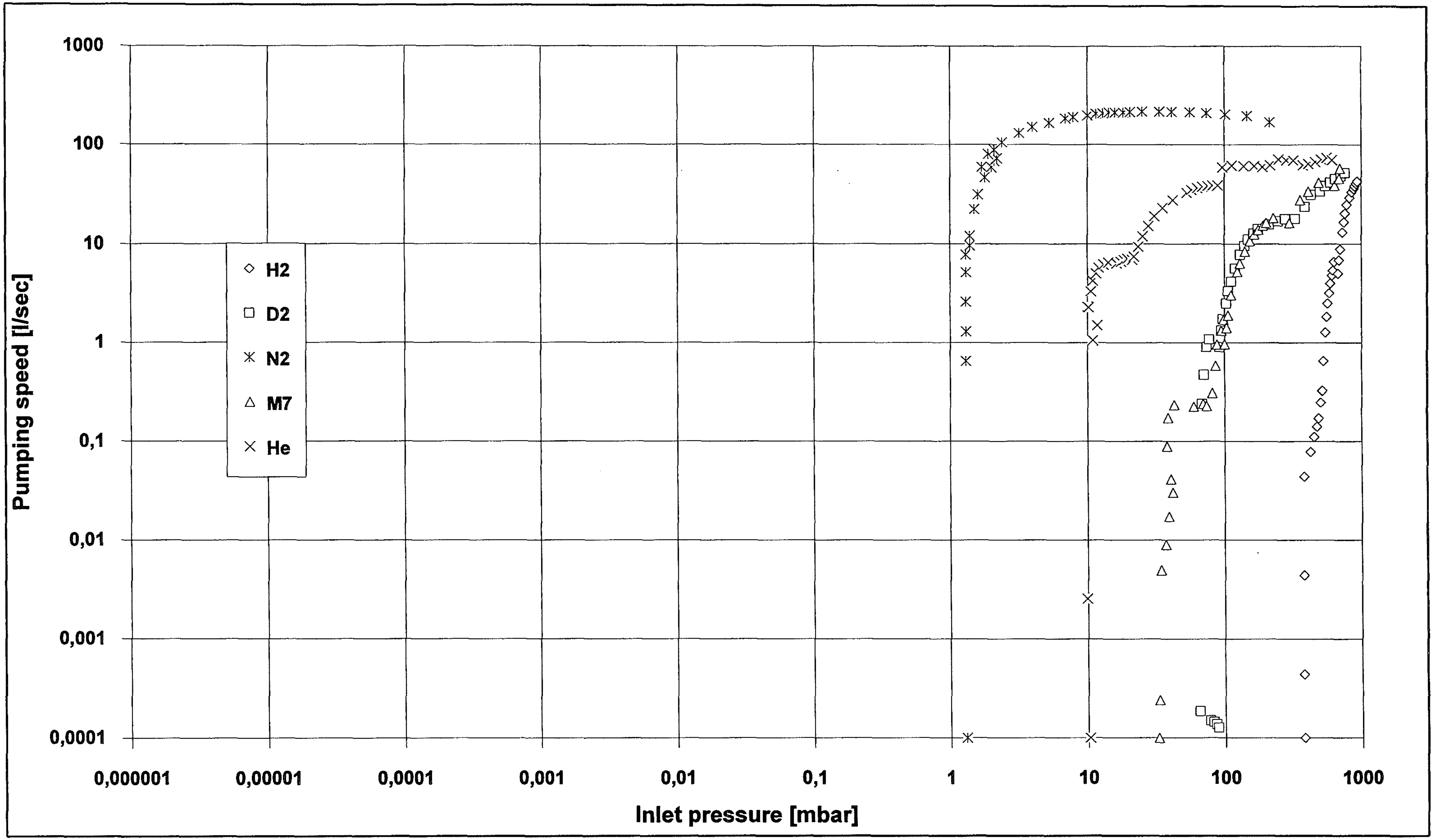


Fig.5: Pumping speed of NORMETEX-1300 pump for various gases at 1200 mbar exhaust pressure

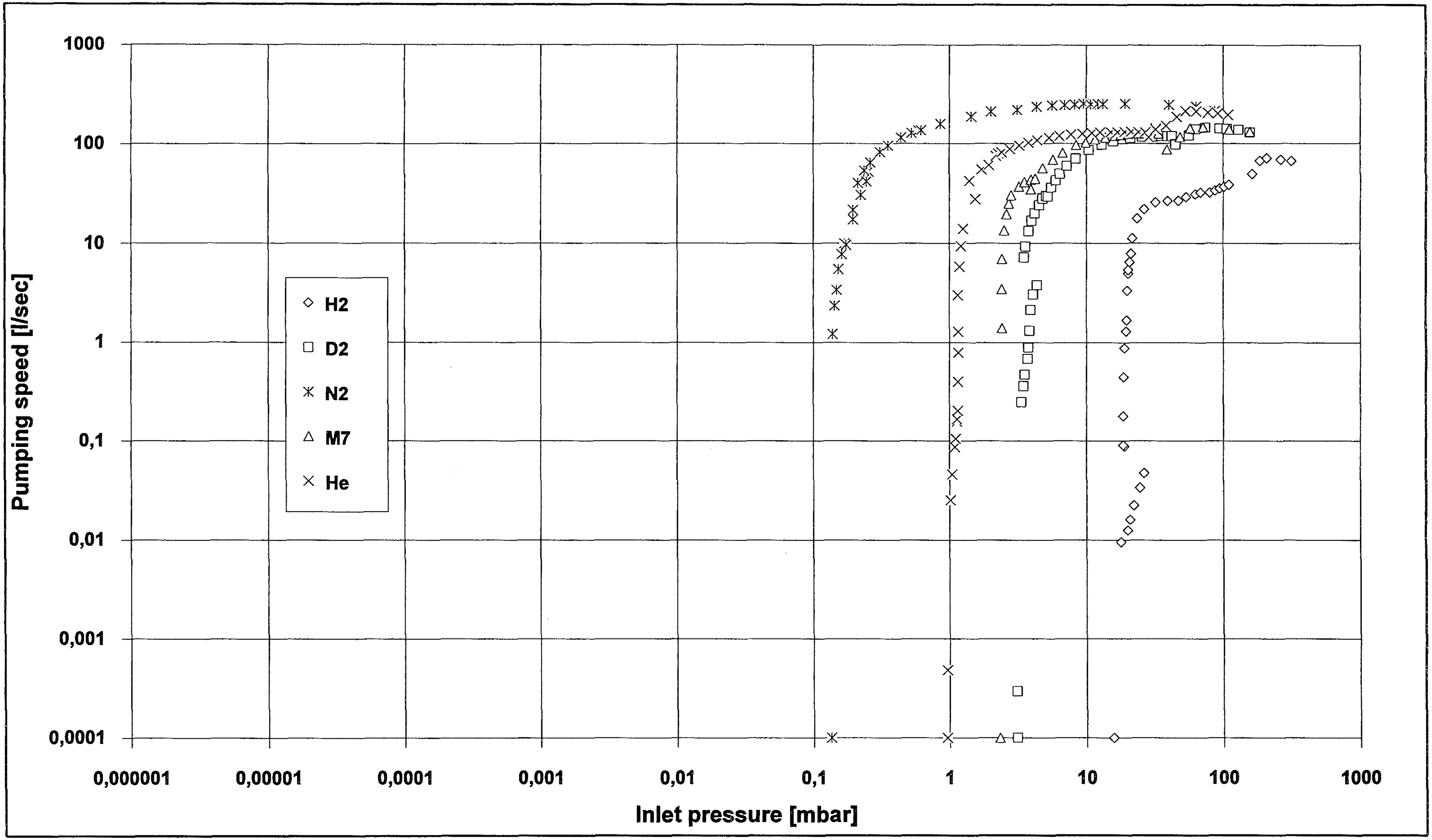


Fig.6: Pumping speed of NORMETEX-1300 pump for various gases at 600 mbar exhaust pressure

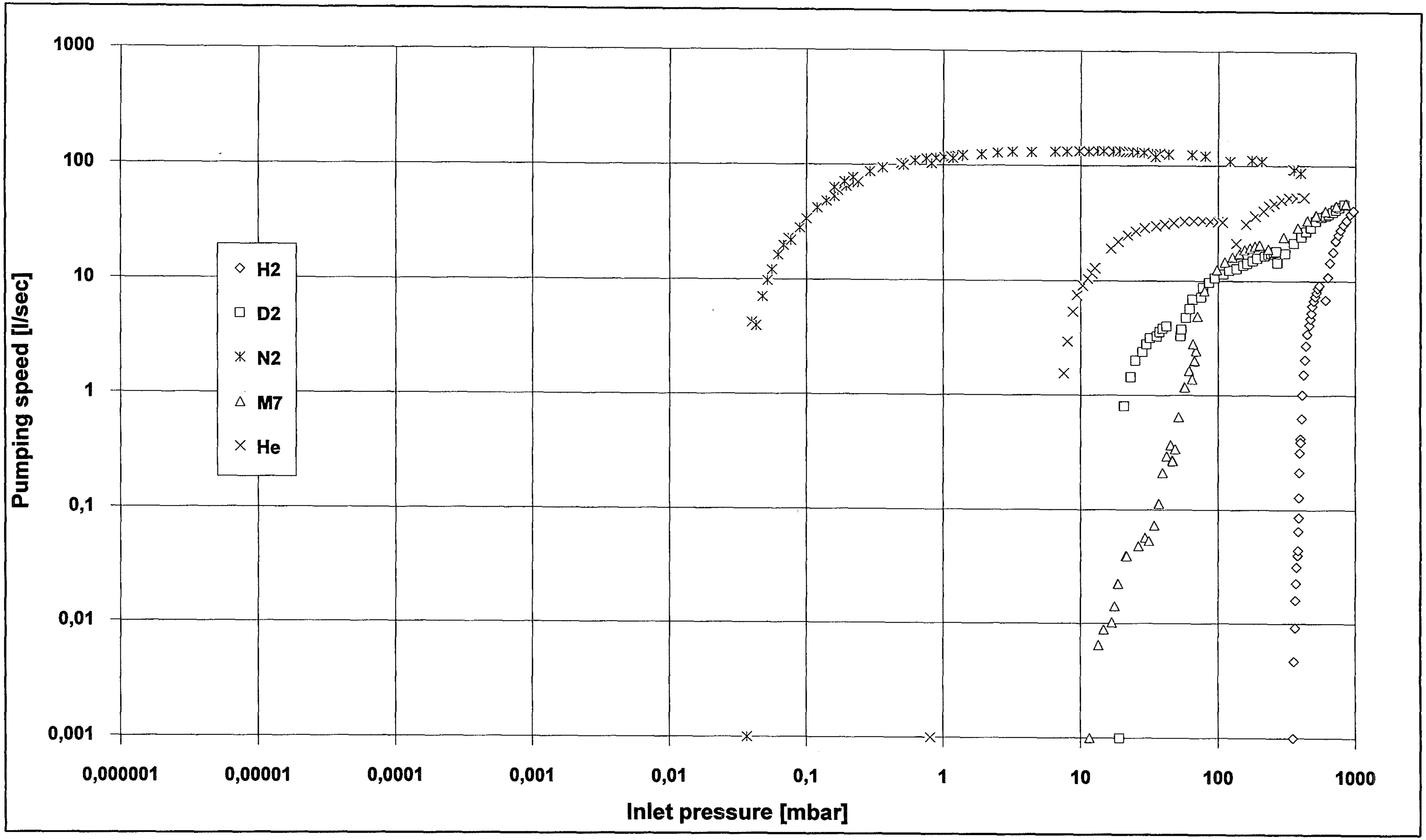


Fig.7: Pumping speed of NORMETEX-600 pump for various gases at 1200 mbar exhaust pressure

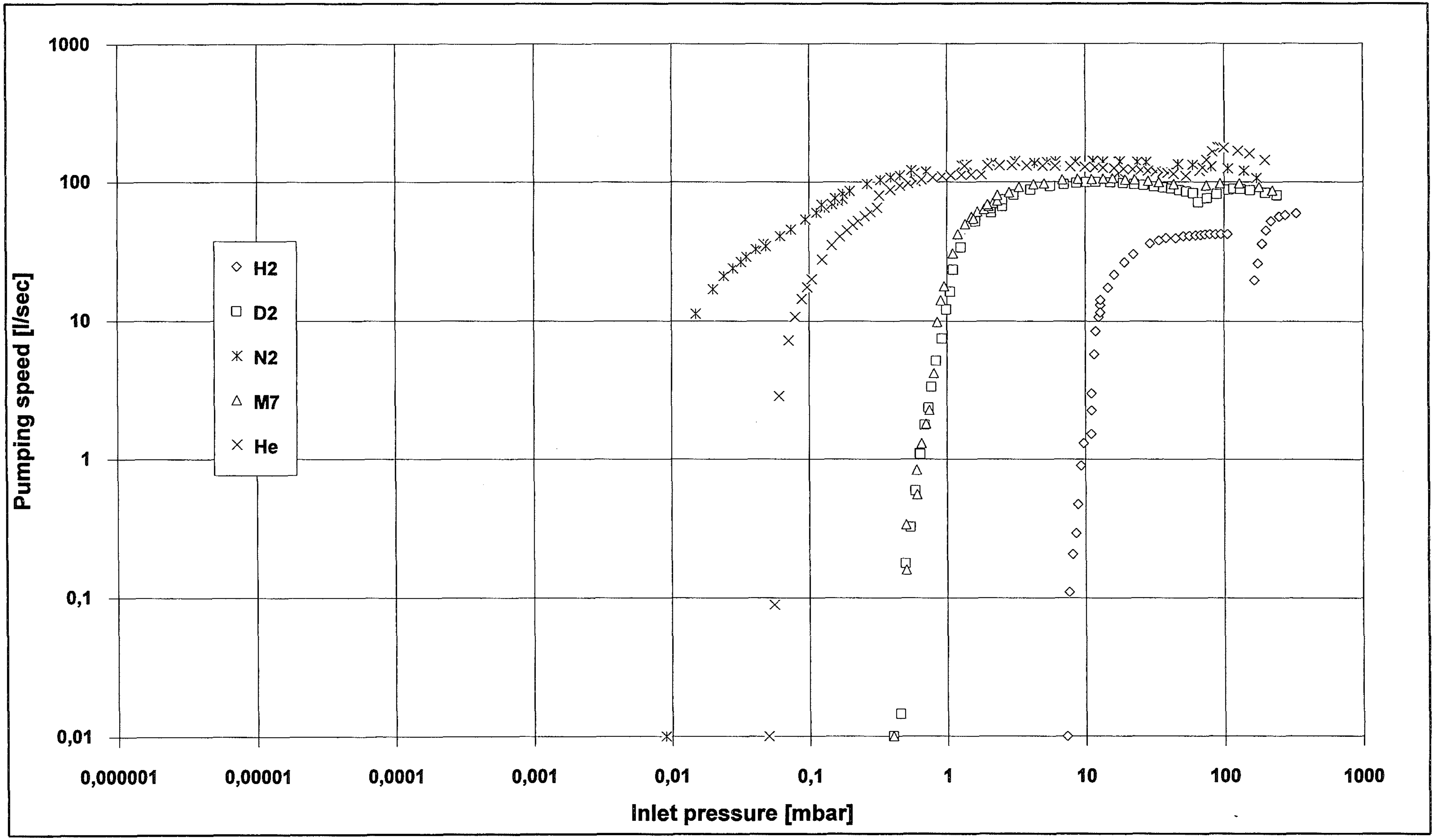


Fig.8: Pumping speed of NORMETEX-600 pump for various gases at 600 mbar exhaust pressure

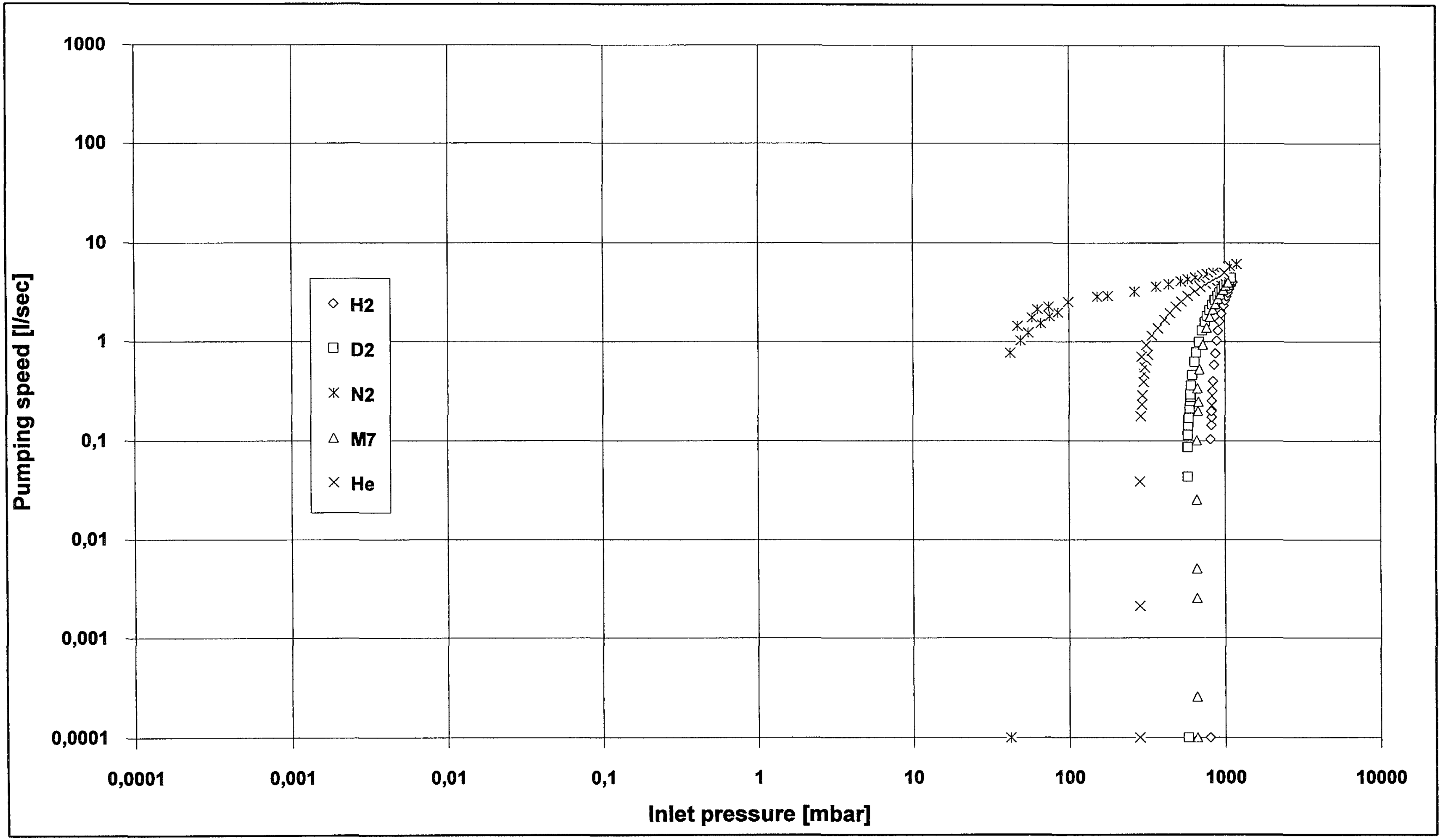


Fig.9: Pumping speed of NORMETEX-60 pump for various gases at 1200 mbar exhaust pressure

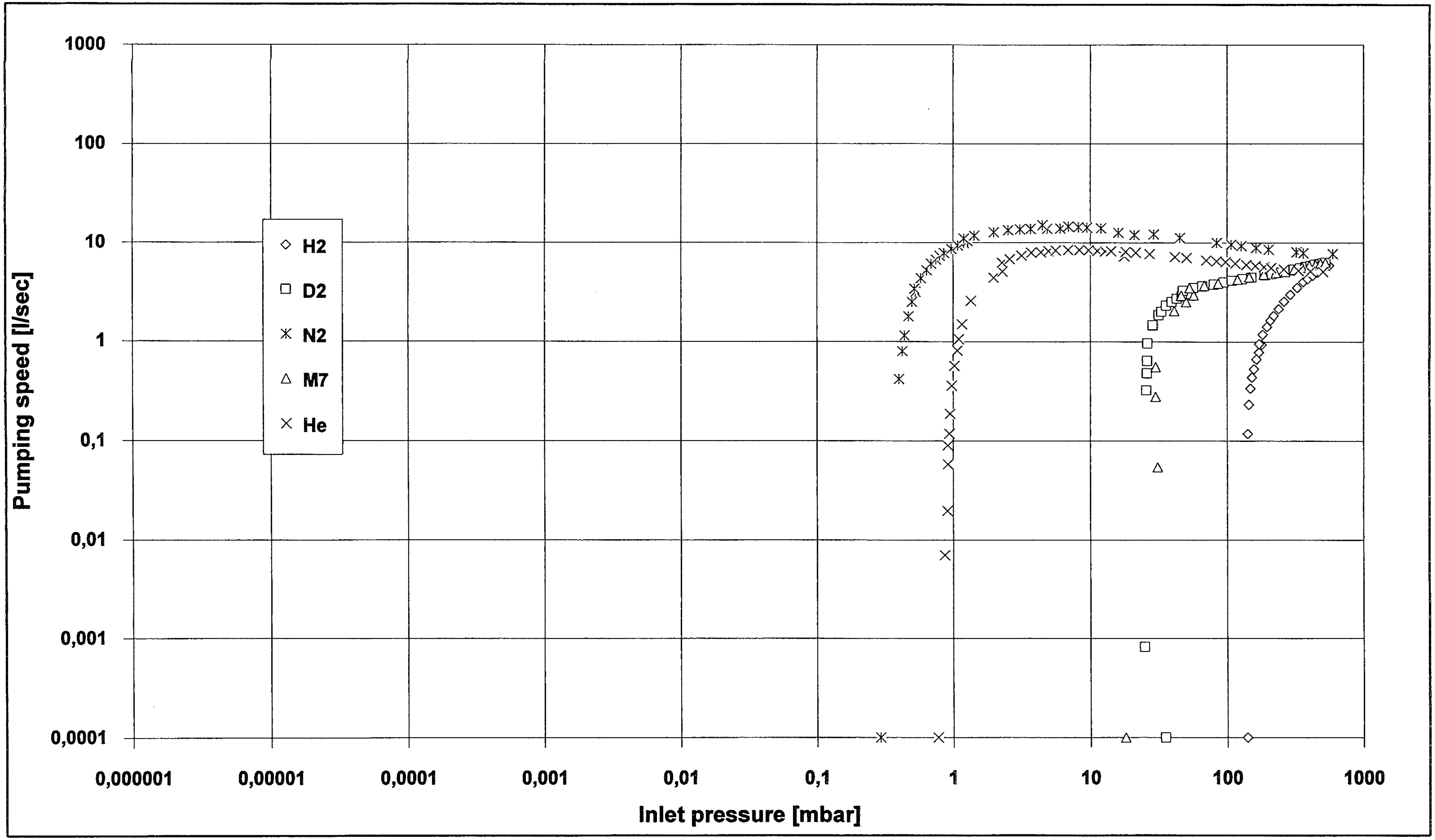


Fig.10: Pumping speed of NORMETEX-60 pump for various gases at 600 mbar exhaust pressure

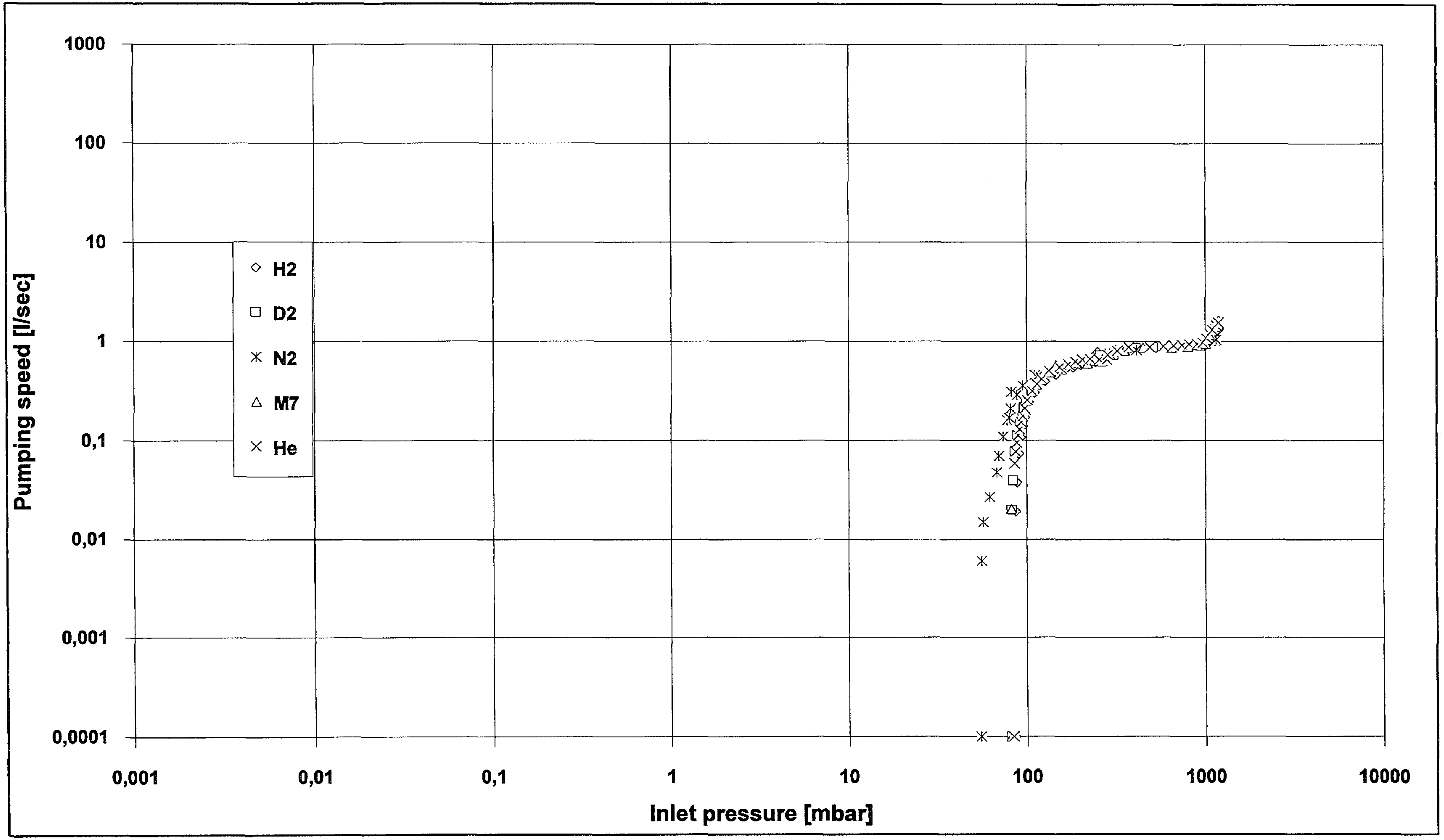


Fig.11: Pumping speed of METAL BELLOWS-6 pump for various gases at 1200 mbar exhaust pressure

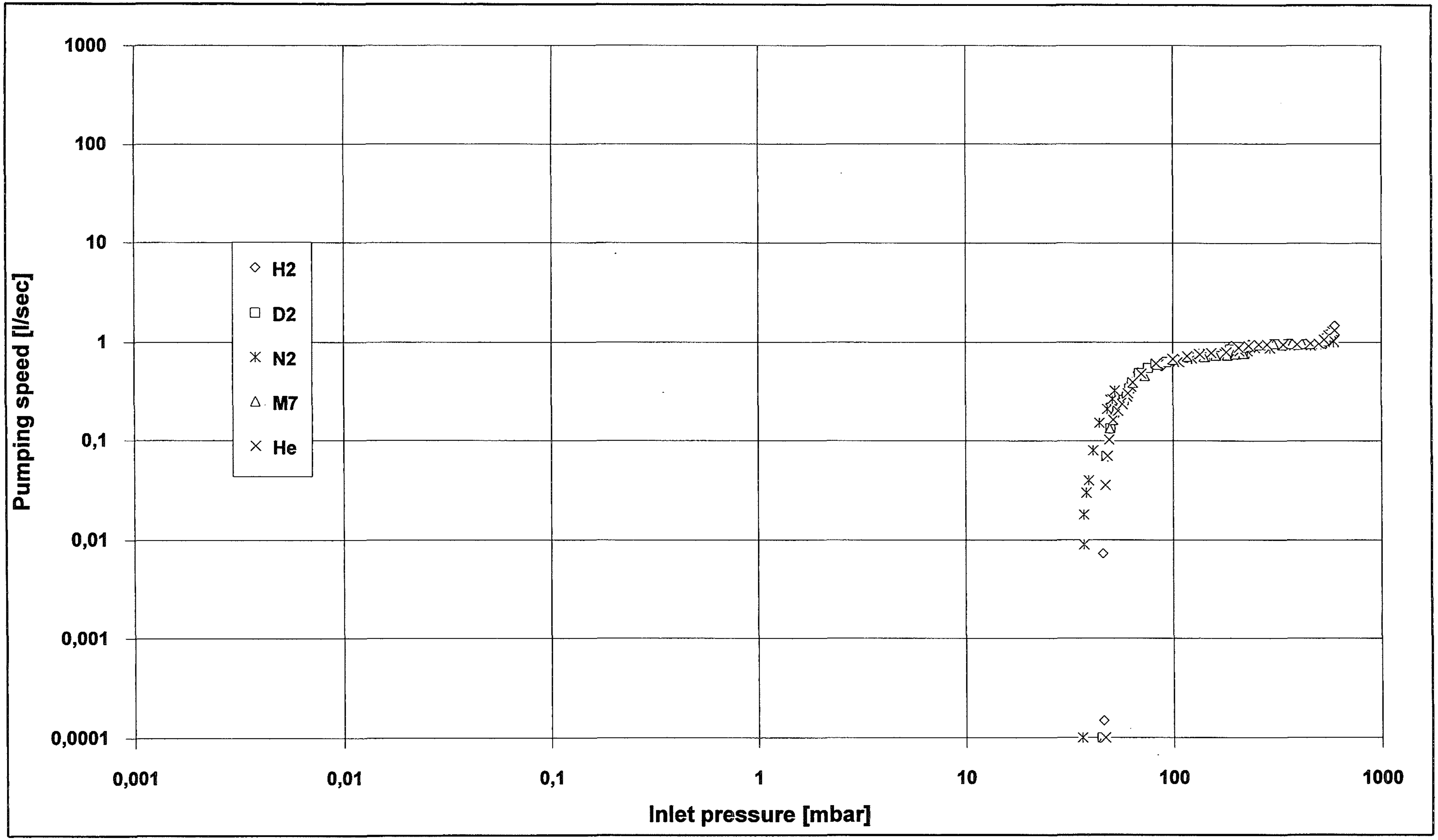


Fig.12: Pumping speed of METAL BELLOWS-6 pump for various gases at 600 mbar exhaust pressure

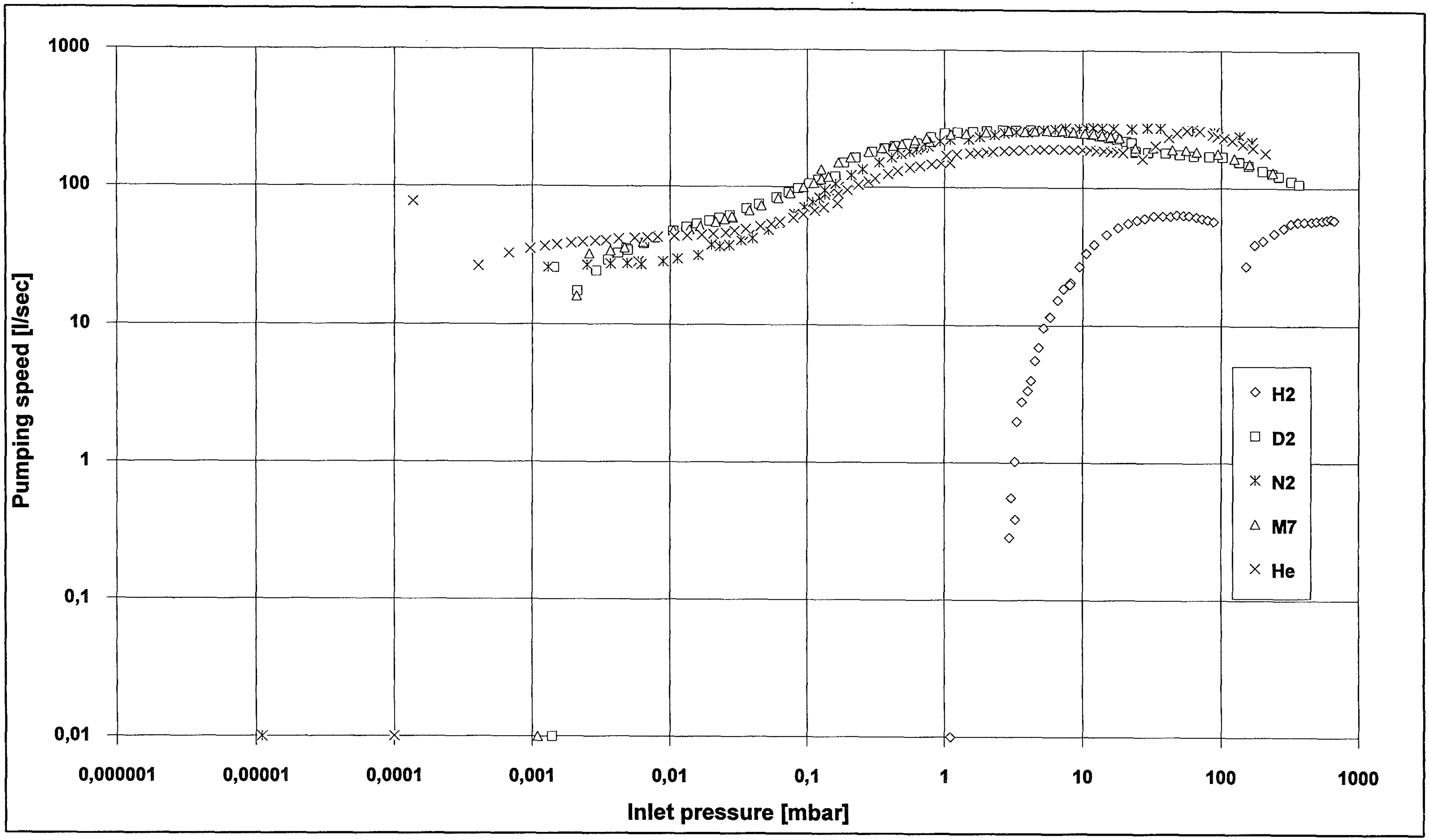


Fig.13: Pumping speed of NORMETEX-1300+600 pump train for various gases at 1200 mbar exhaust pressure

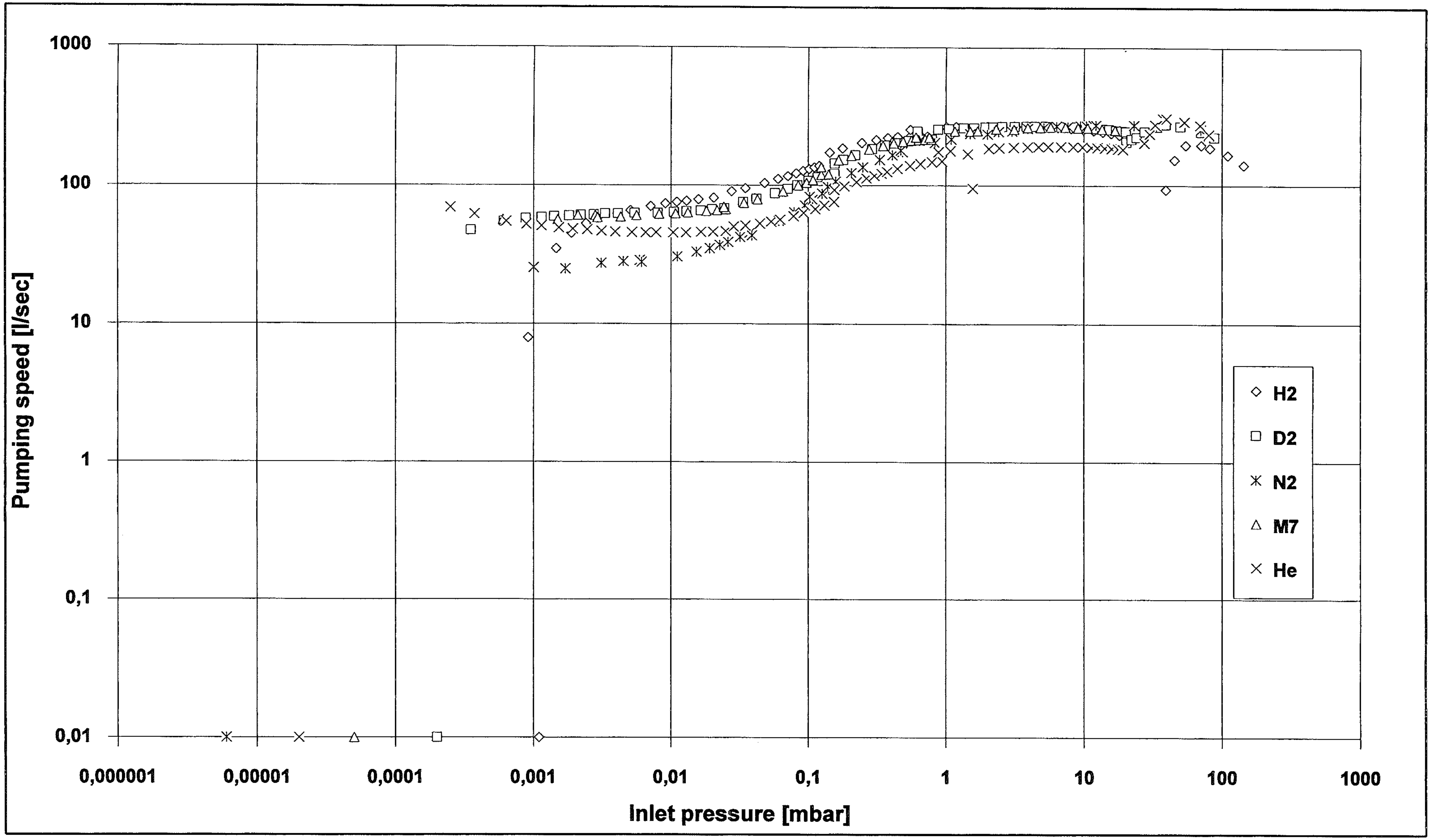


Fig.14: Pumping speed of NORMETEX-1300+600 pump train for various gases at 600 mbar exhaust pressure

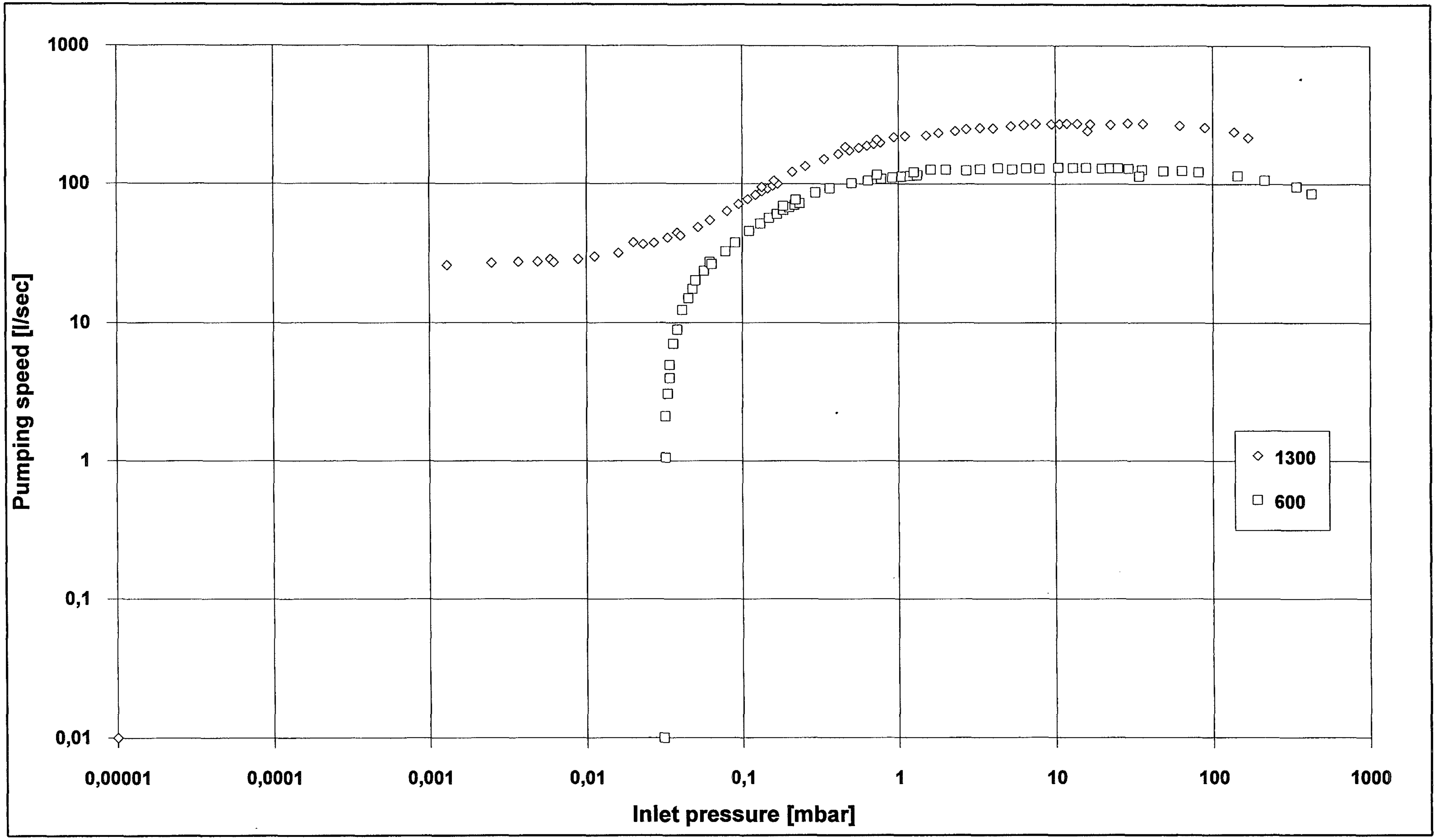


Fig.15: Pumping speed at the inlet of pumps of NORMETEX-1300+600 pump train for N2 at 1200 mbar exhaust pressure

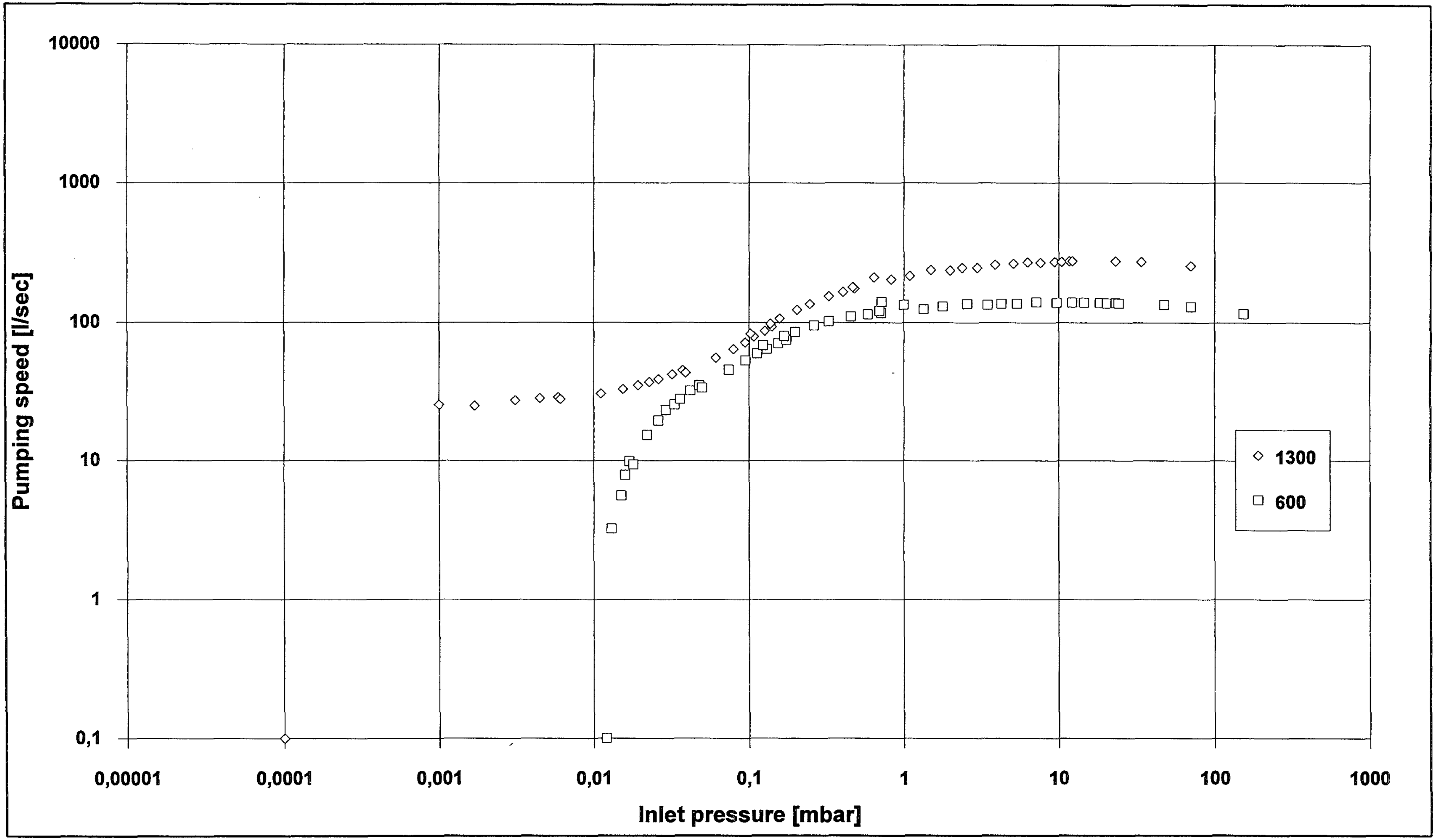


Fig.16: Pumping speed at the inlet of pumps of NORMETEX-1300+600 pump train for N2 at 600 mbar exhaust pressure

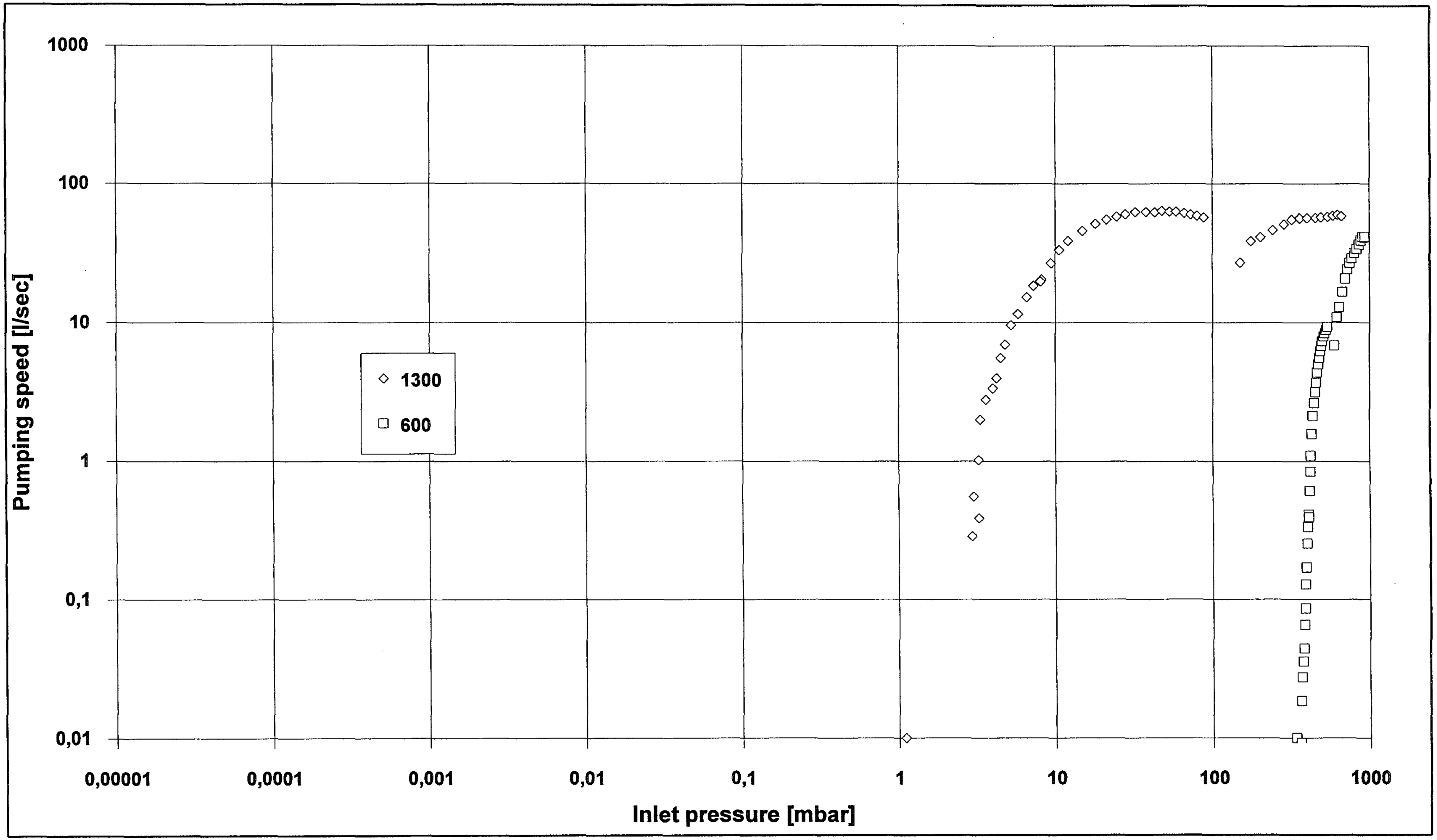


Fig.17: Pumping speed at the inlet of pumps of NORMETEX-1300+600 pump train for H2 at 1200 mbar exhaust pressure

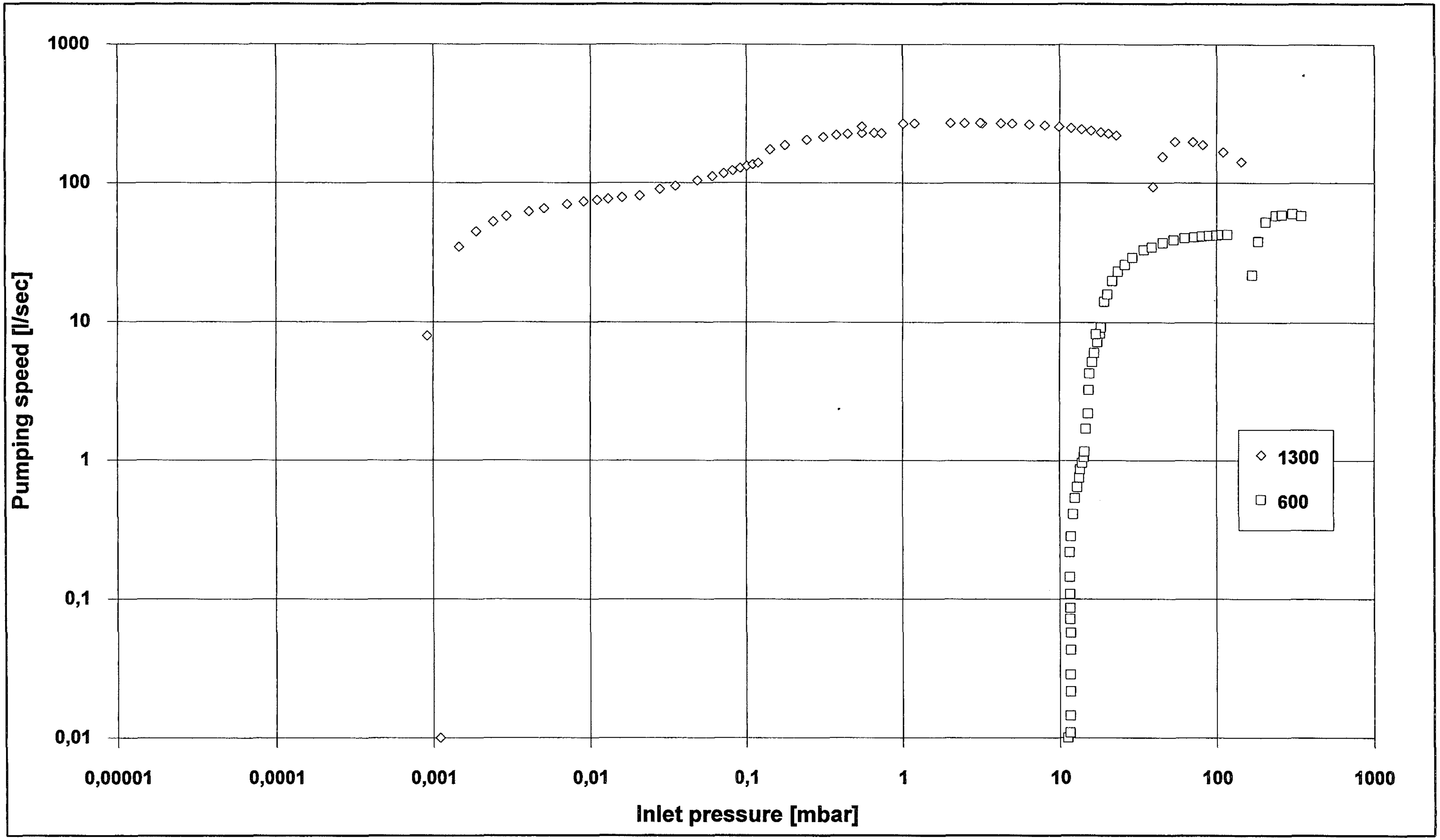


Fig.18: Pumping speed at the inlet of pumps of NORMETEX-1300+600 pump train for H2 at 600 mbar exhaust pressure

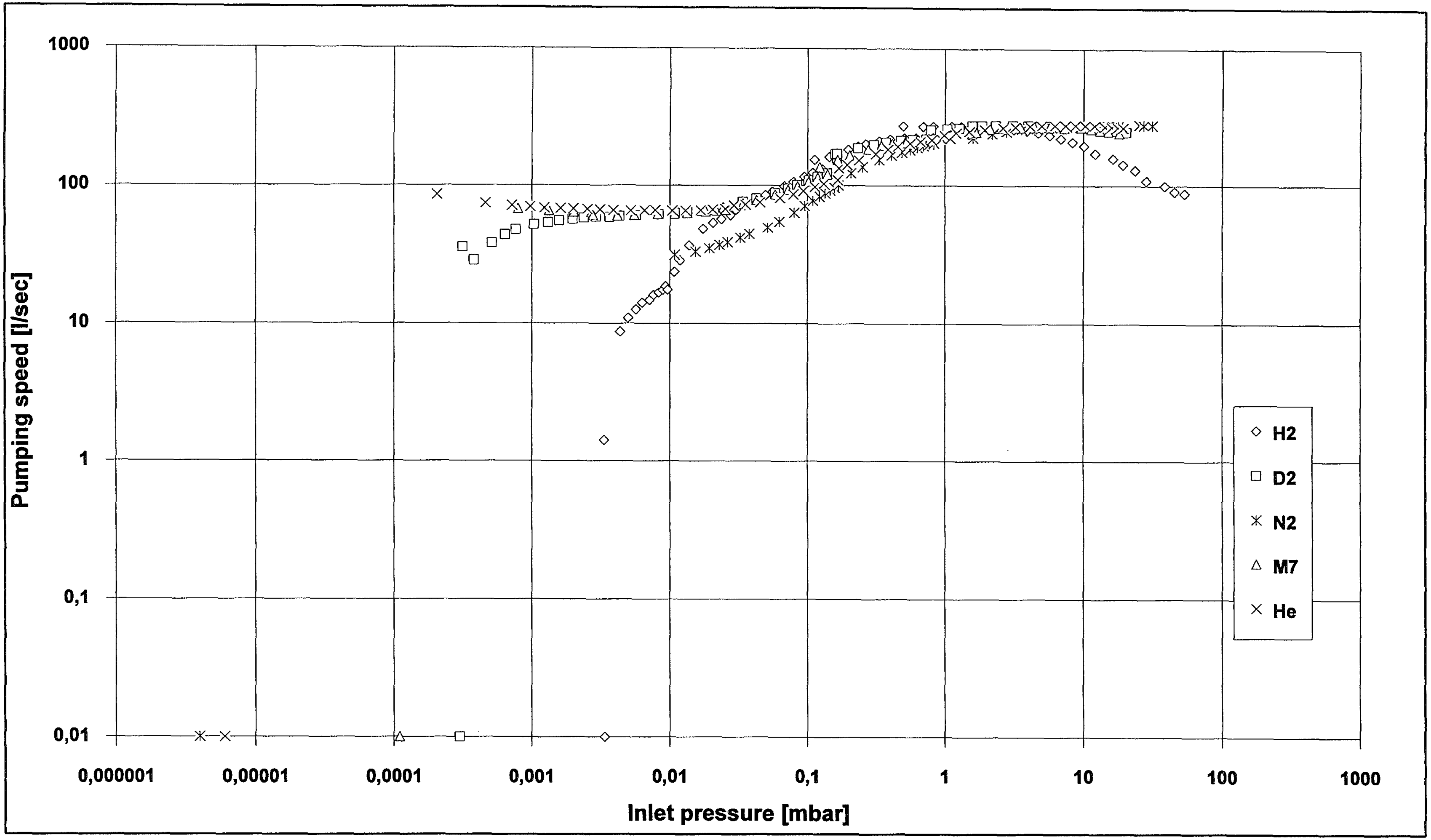


Fig.19: Pumping speed of NORMETEX-1300+600+60 pump train for various gases at 1200 mbar exhaust pressure

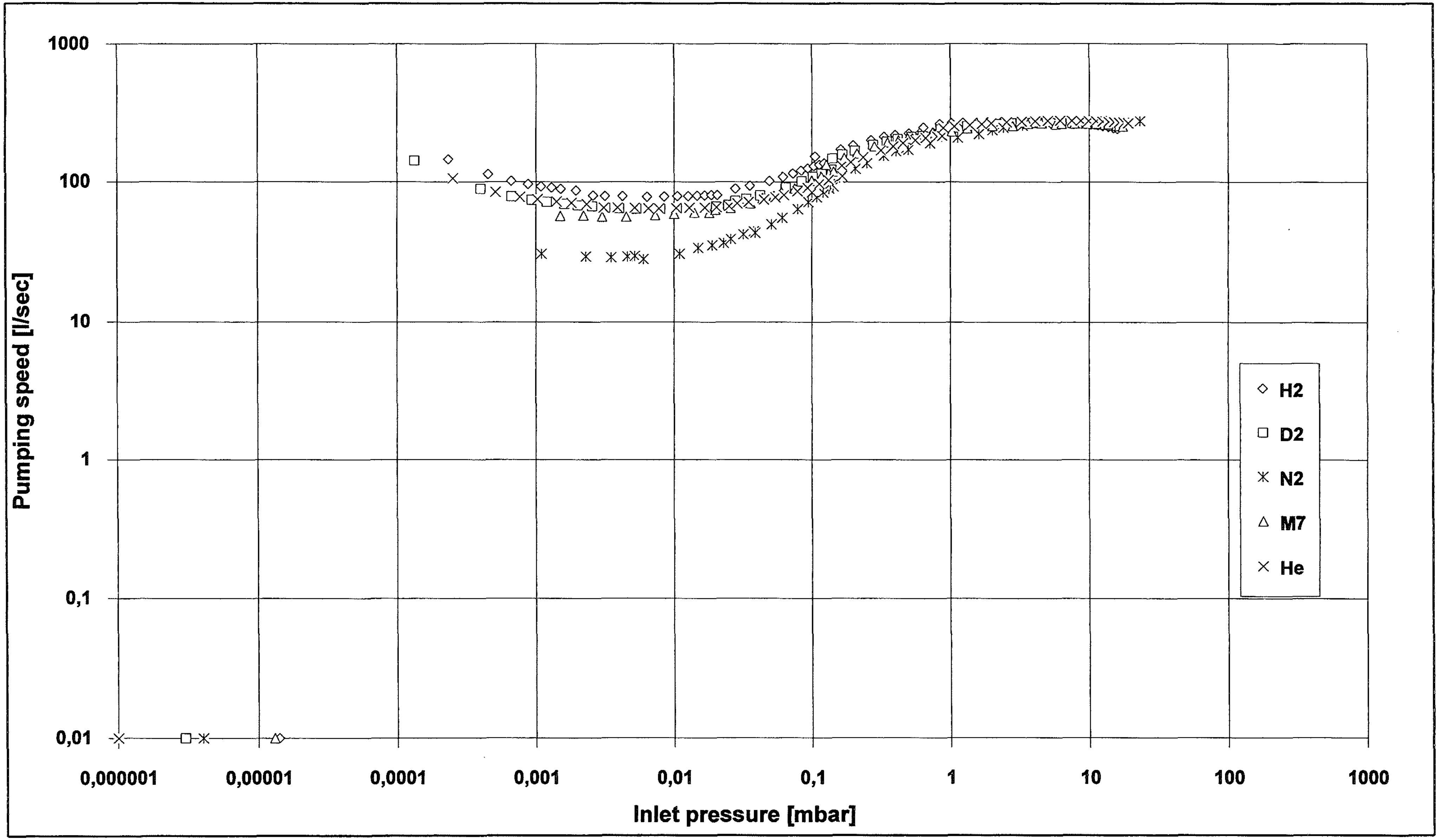


Fig.20: Pumping speed of NORMETEX-1300+600+60 pump train for various gases at 600 mbar exhaust pressure

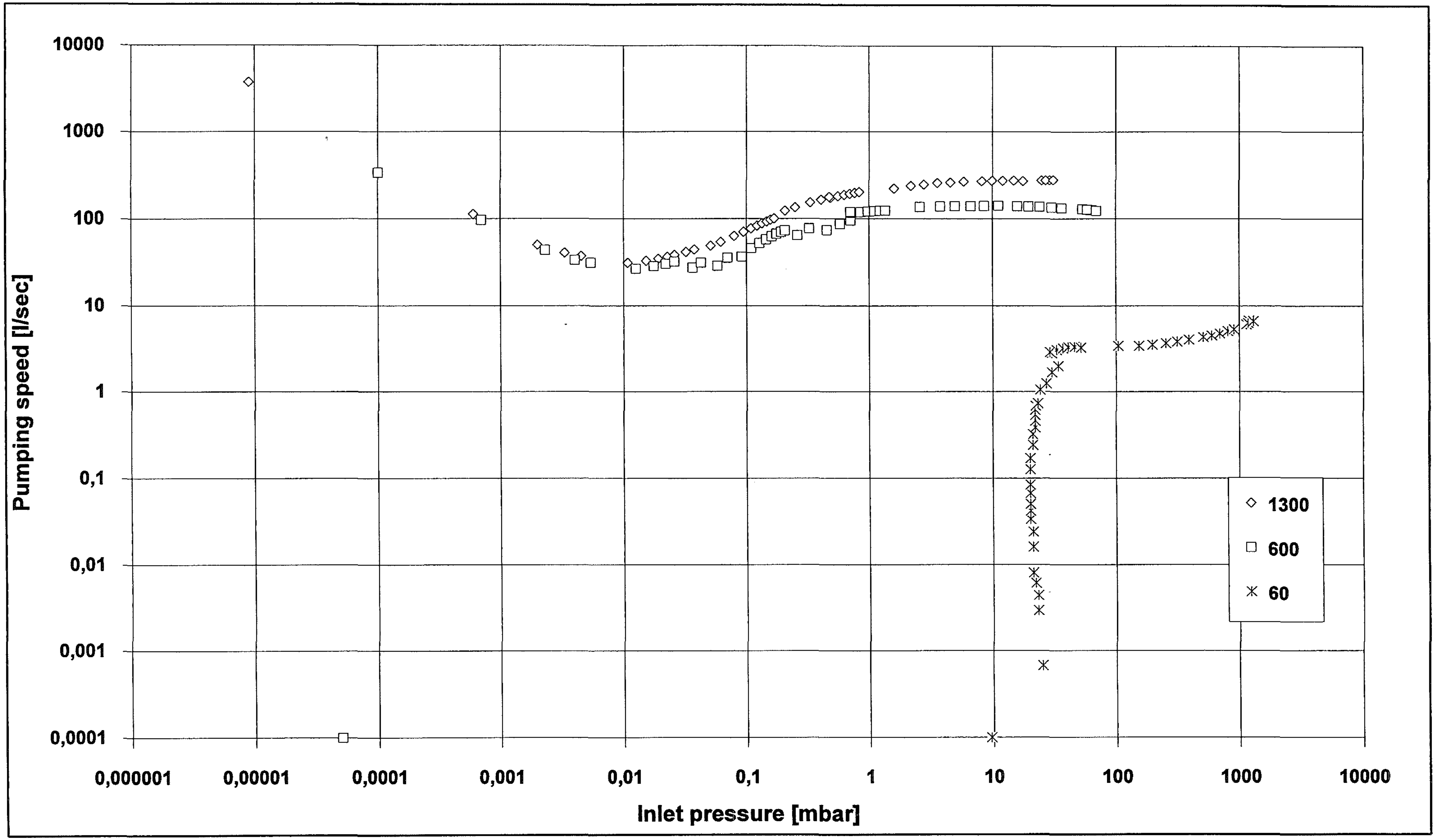


Fig.21: Pumping speed at the inlet of pumps of NORMETEX-1300+600+60 pump train for N2 at 1200 mbar exhaust pressure

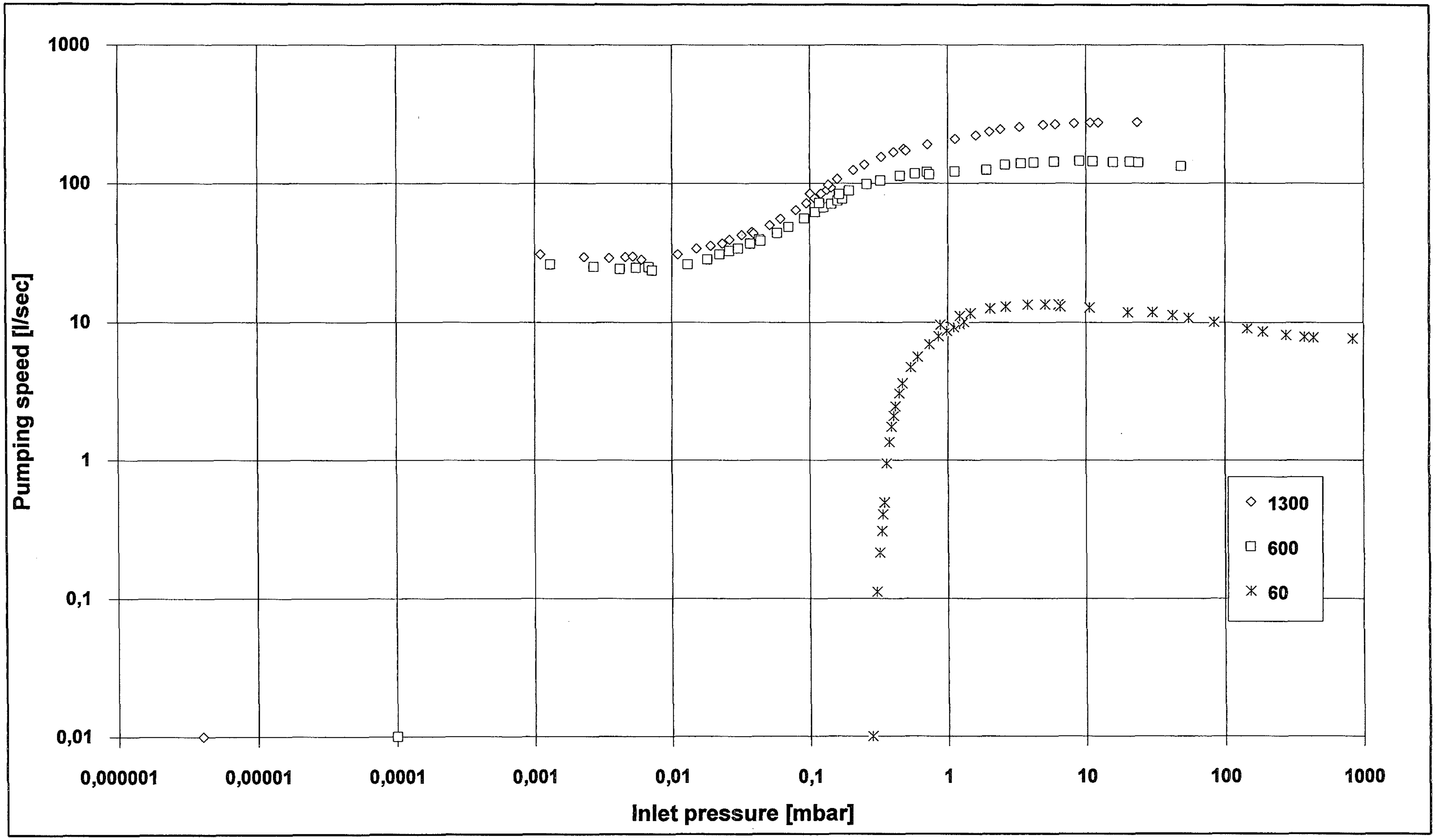


Fig.22: Pumping speed of the inlet of pumps of NORMETEX-1300+600+60 pump train for N2 at 600 mbar exhaust pressure

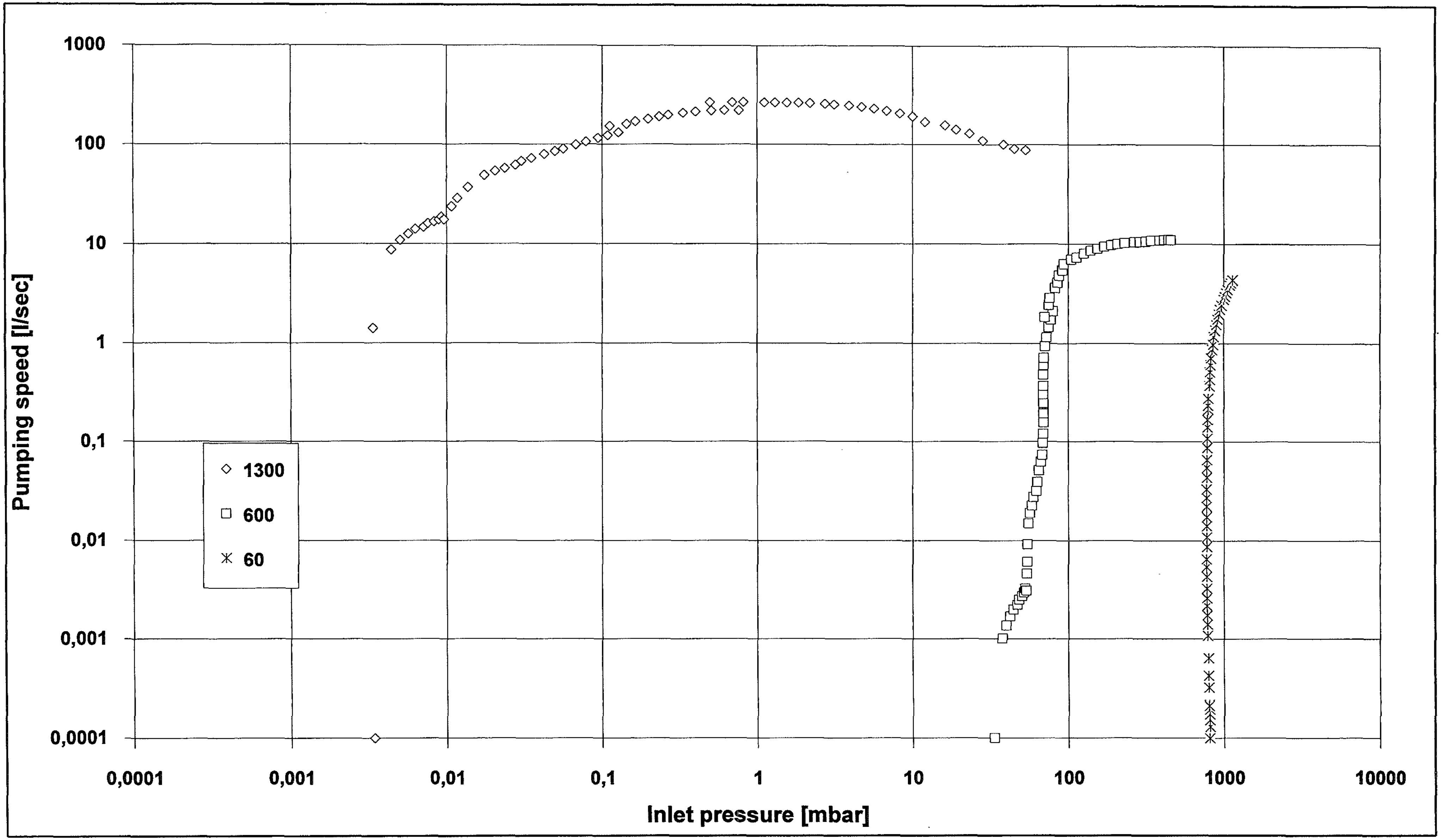


Fig.23: Pumping speed of the inlet of pumps of NORMETEX-1300+600+60 pump train for H2 at 1200 mbar exhaust pressure

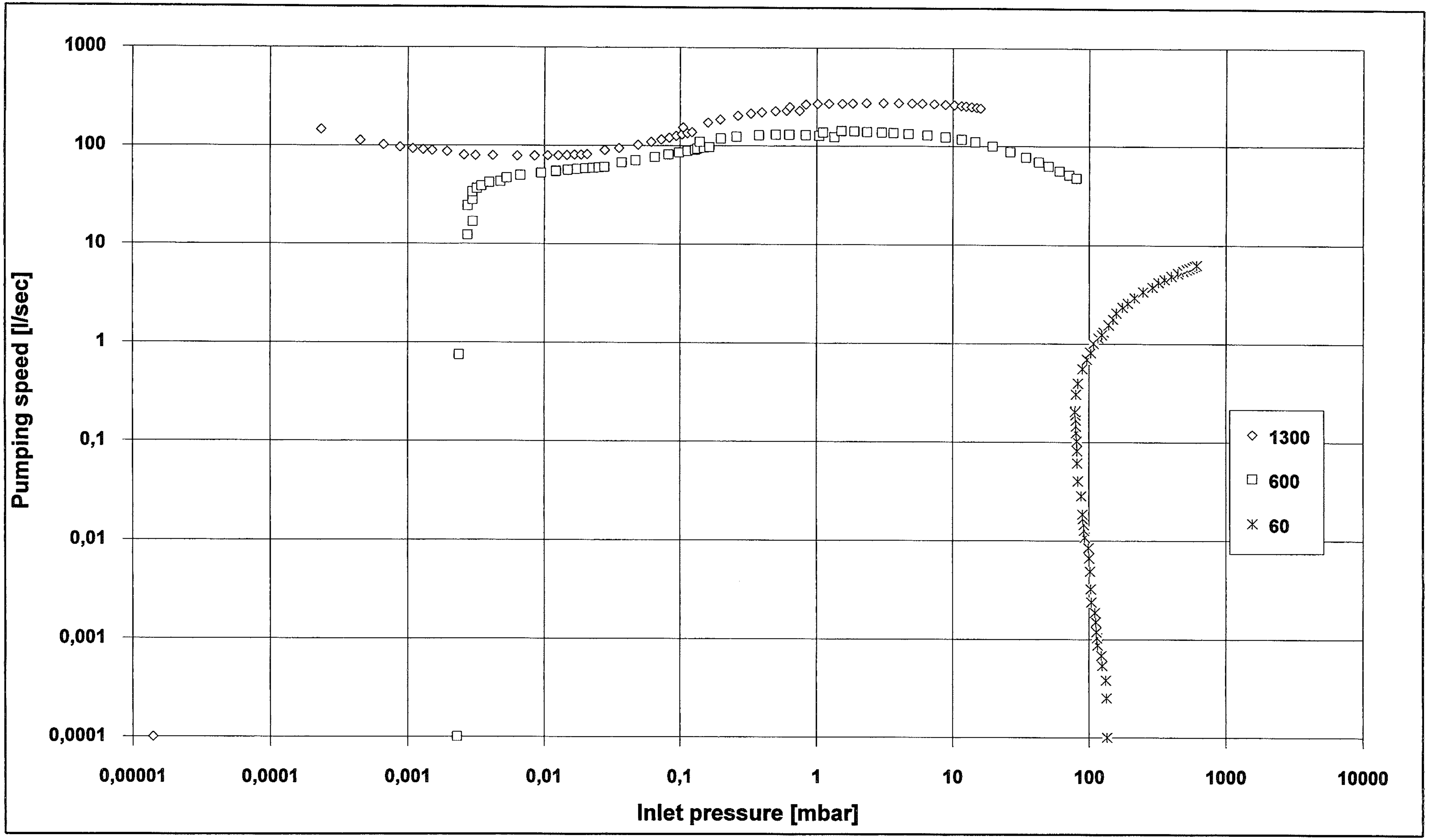


Fig.24: Pumping speed at the inlet of pumps of NORMETEX-1300+600+60 pump train for H2 at 600 mbar exhaust pressure

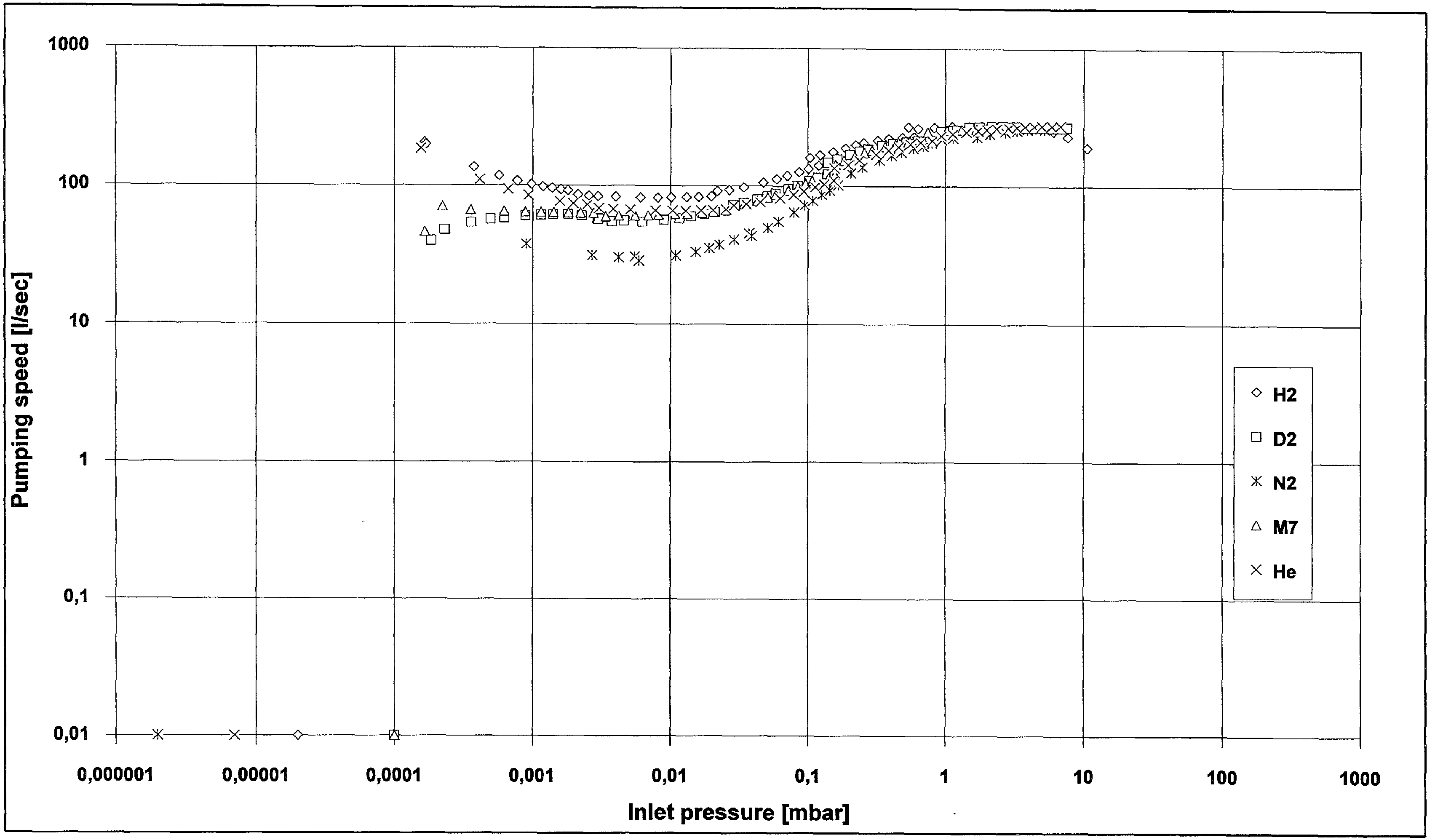


Fig.25: Pumping speed of NORMETEX-1300+600+60+ METAL BELLOWS-6 pump train for various gases at 1200 mbar exhaust pressure

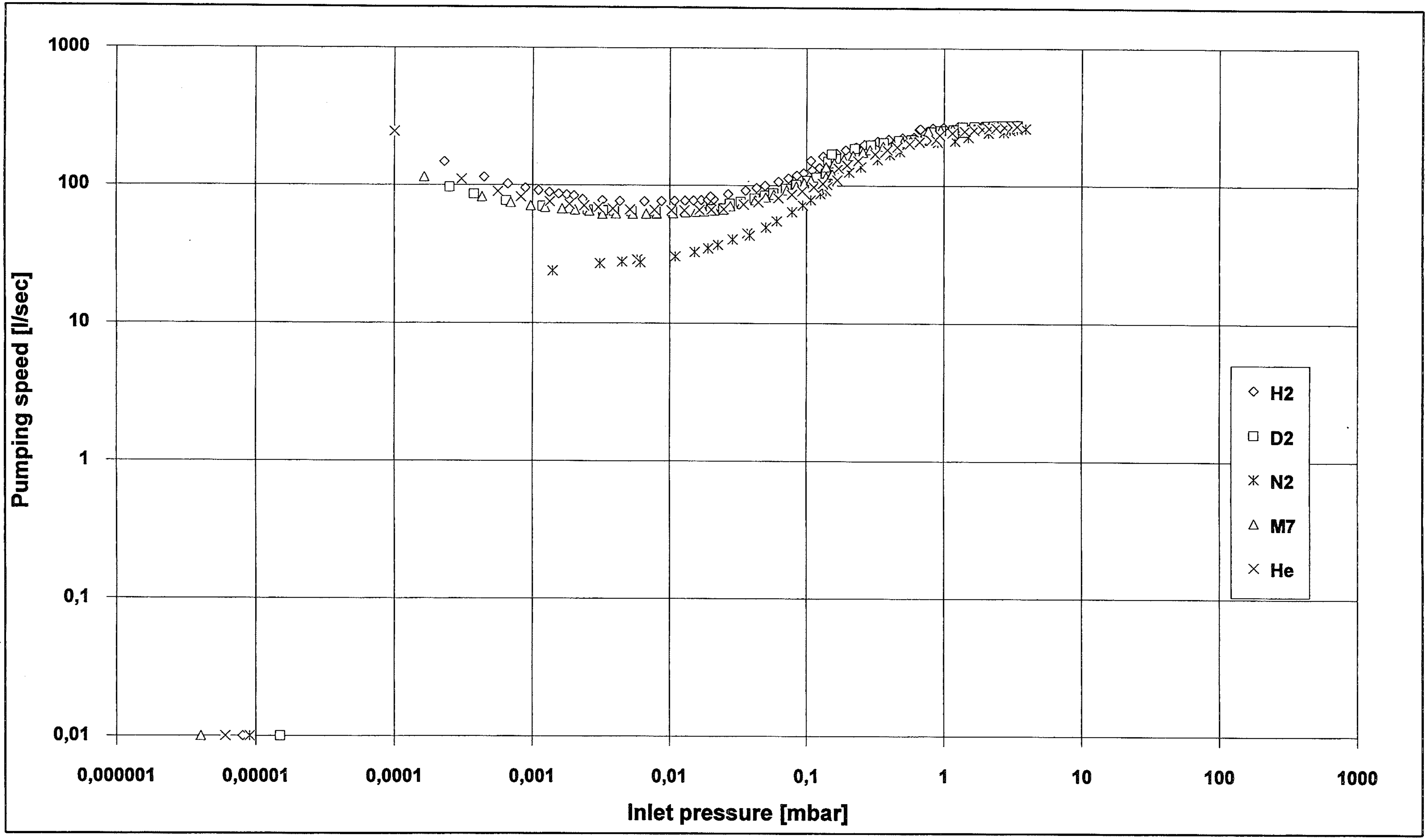


Fig.26: Pumping speed of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for various gases at 600 mbar exhaust pressure

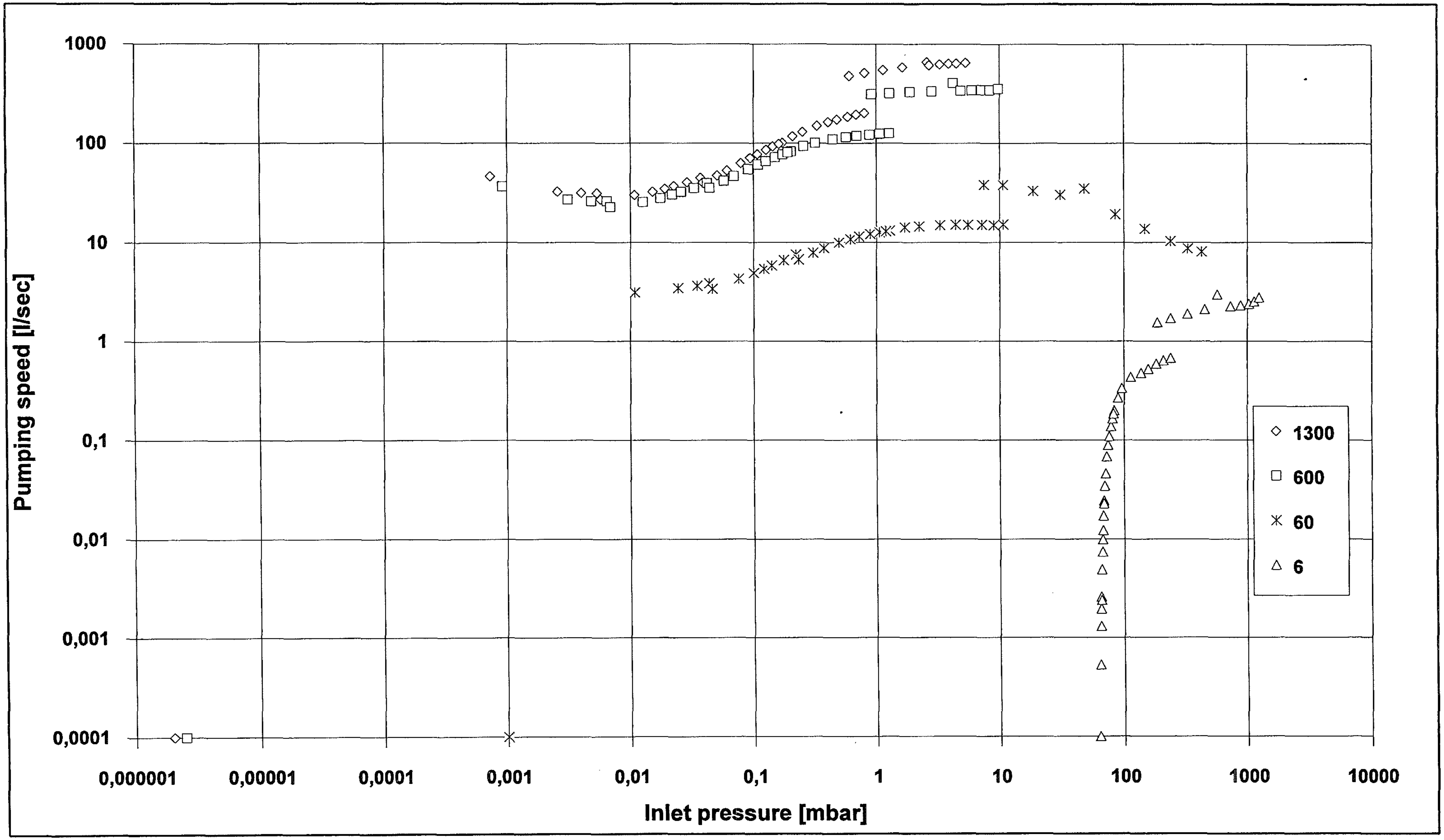


Fig.27: Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for N2 at 1200 mbar exhaust pressure

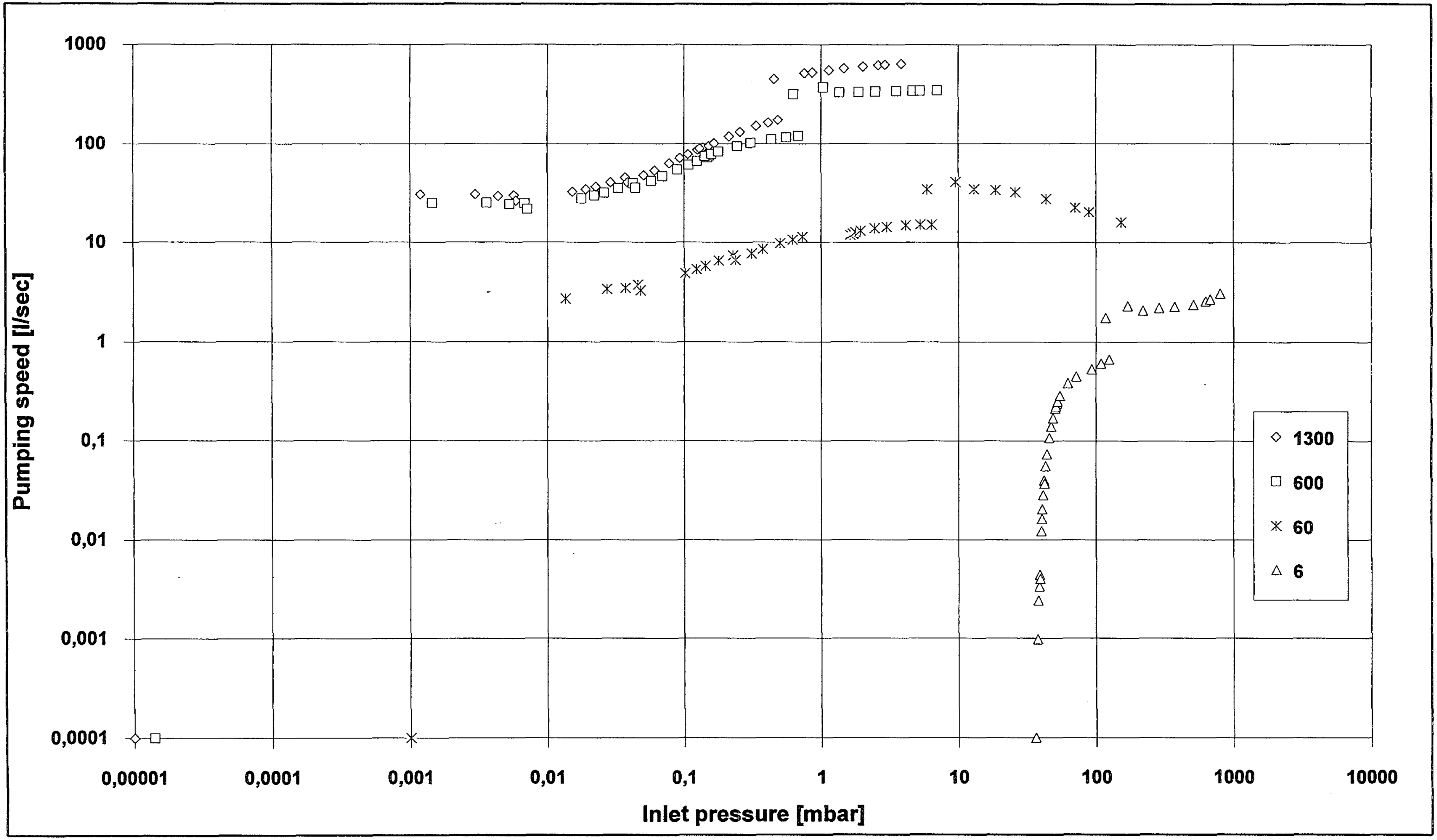


Fig.28: Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for N2 at 600 mbar exhaust pressure

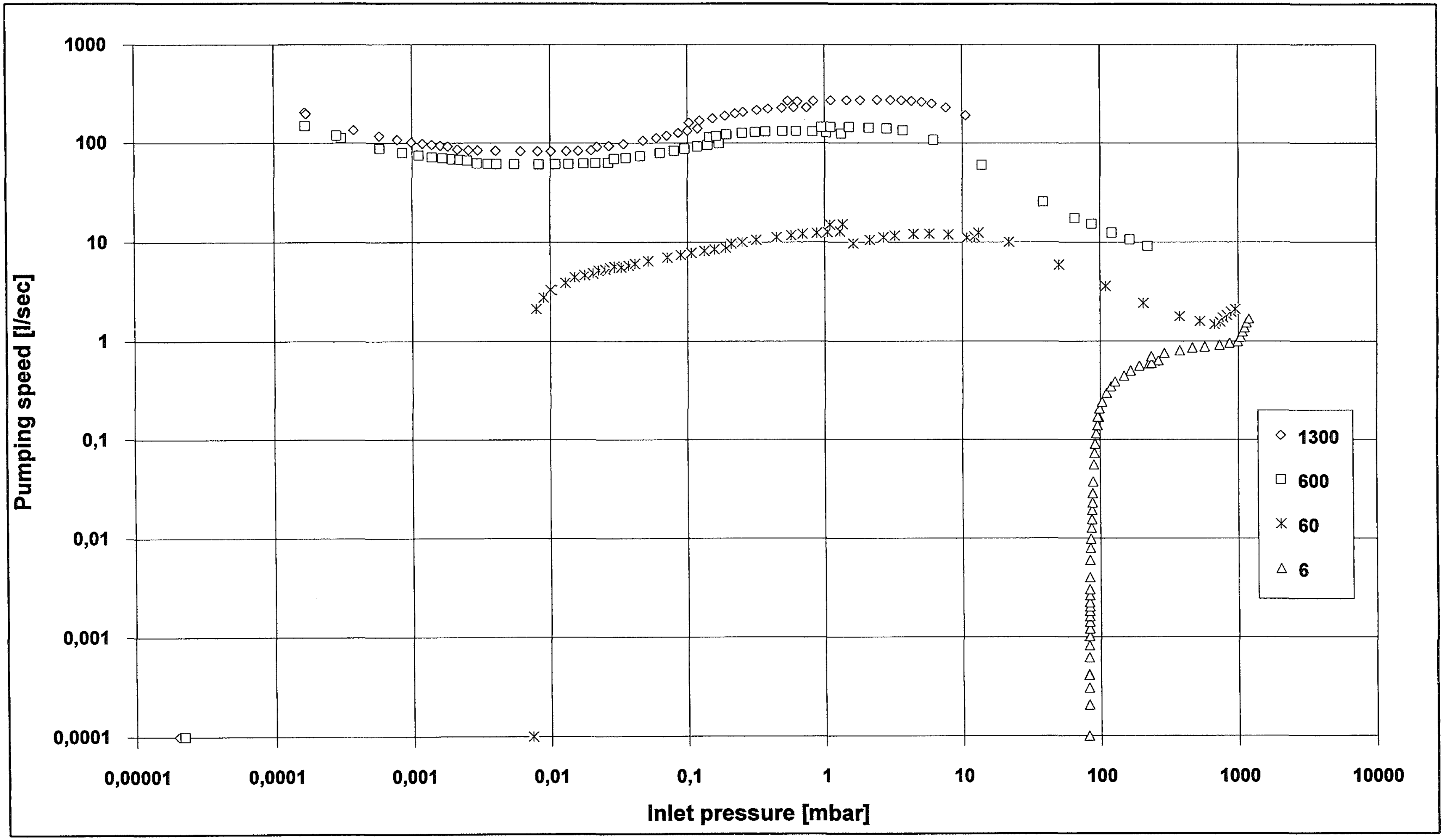


Fig.29: Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for H2 at 1200 mbar exhaust pressure

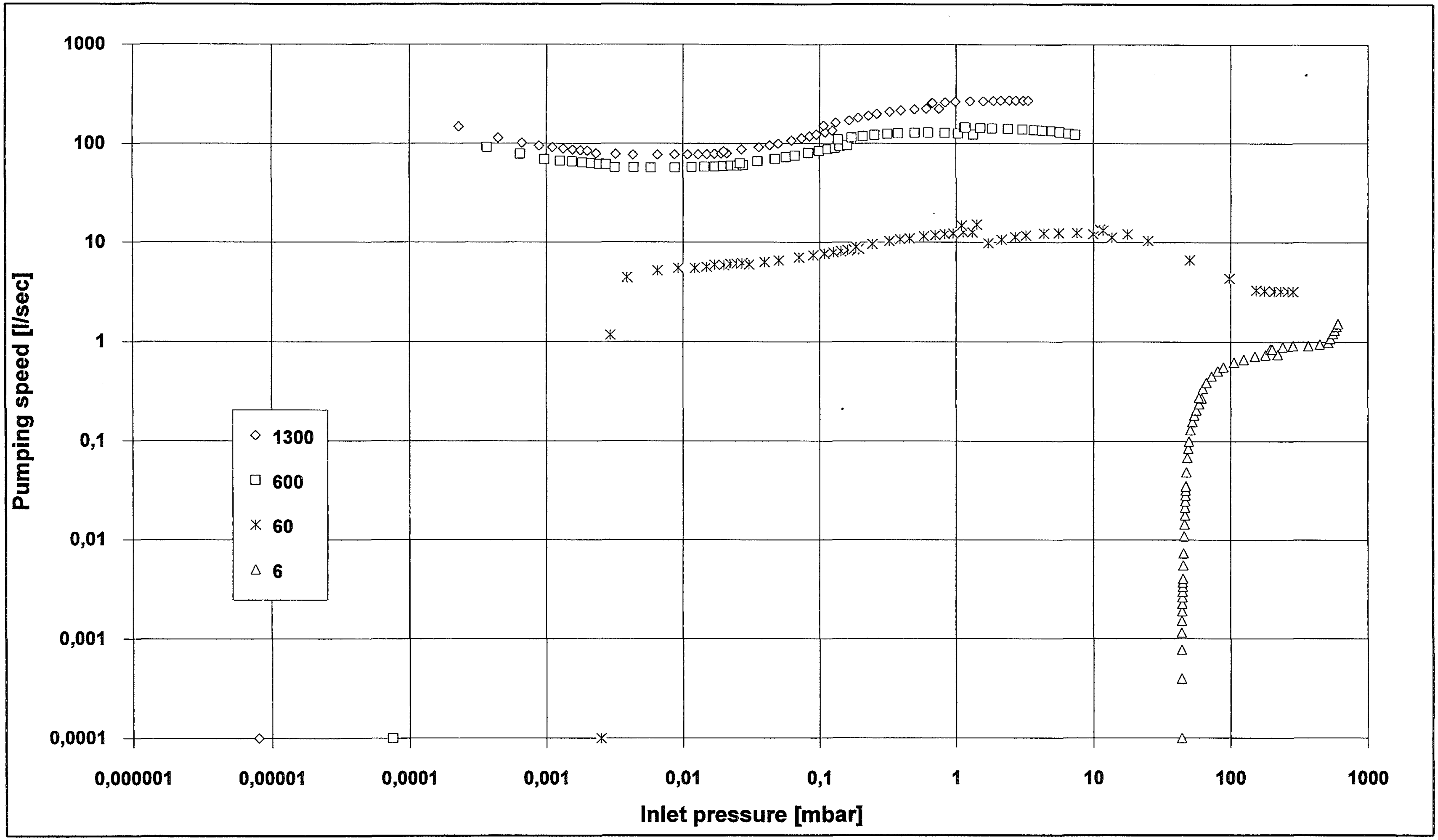


Fig.30: Pumping speed at the inlet of pumps of NORMETEX-1300+600+60+METAL BELLOWS-6 pump train for H2 at 600 mbar exhaust pressure

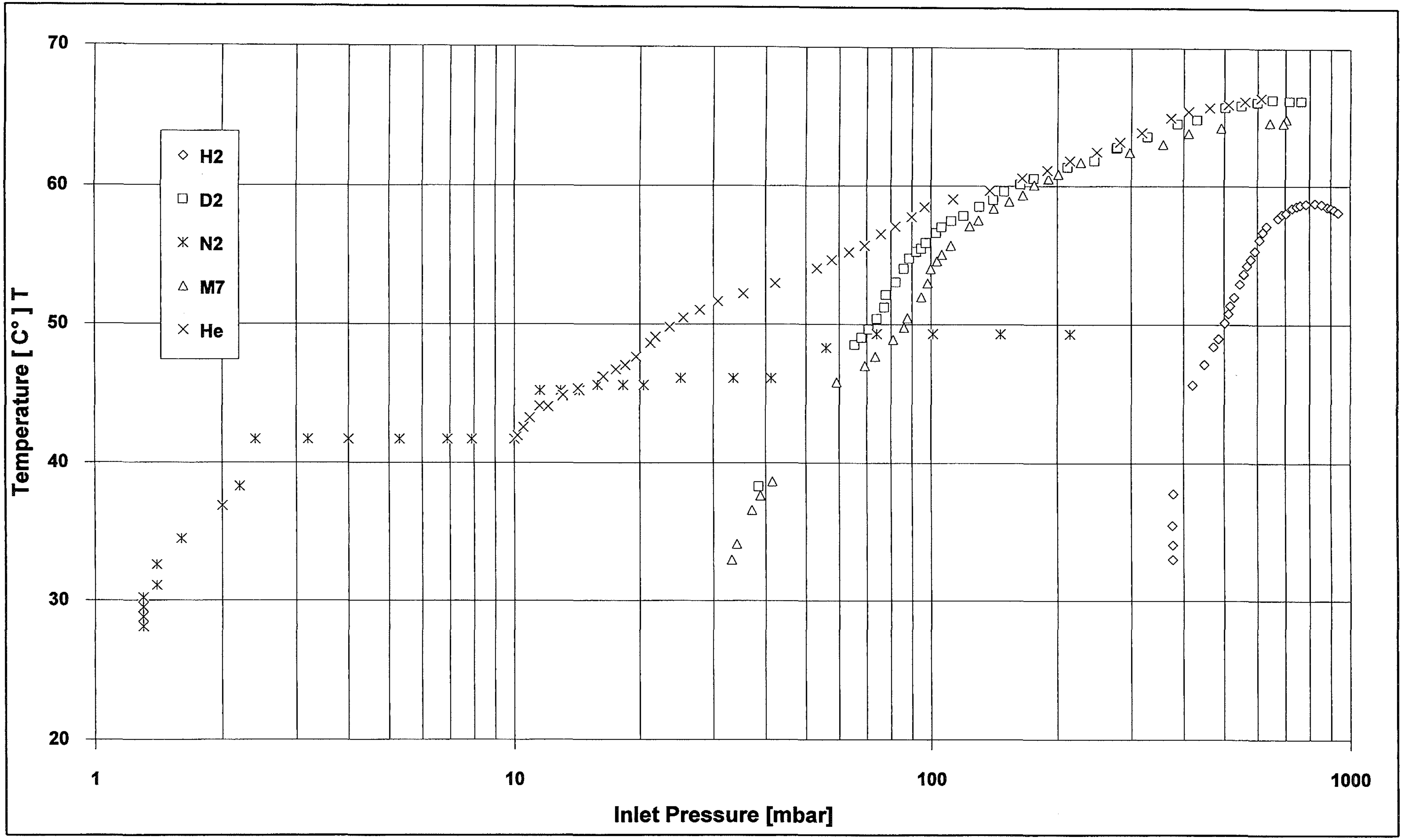


Fig.31: Oil temperature of NORMETEX 1300 pump for various gases at 1200 mbar exhaust pressure

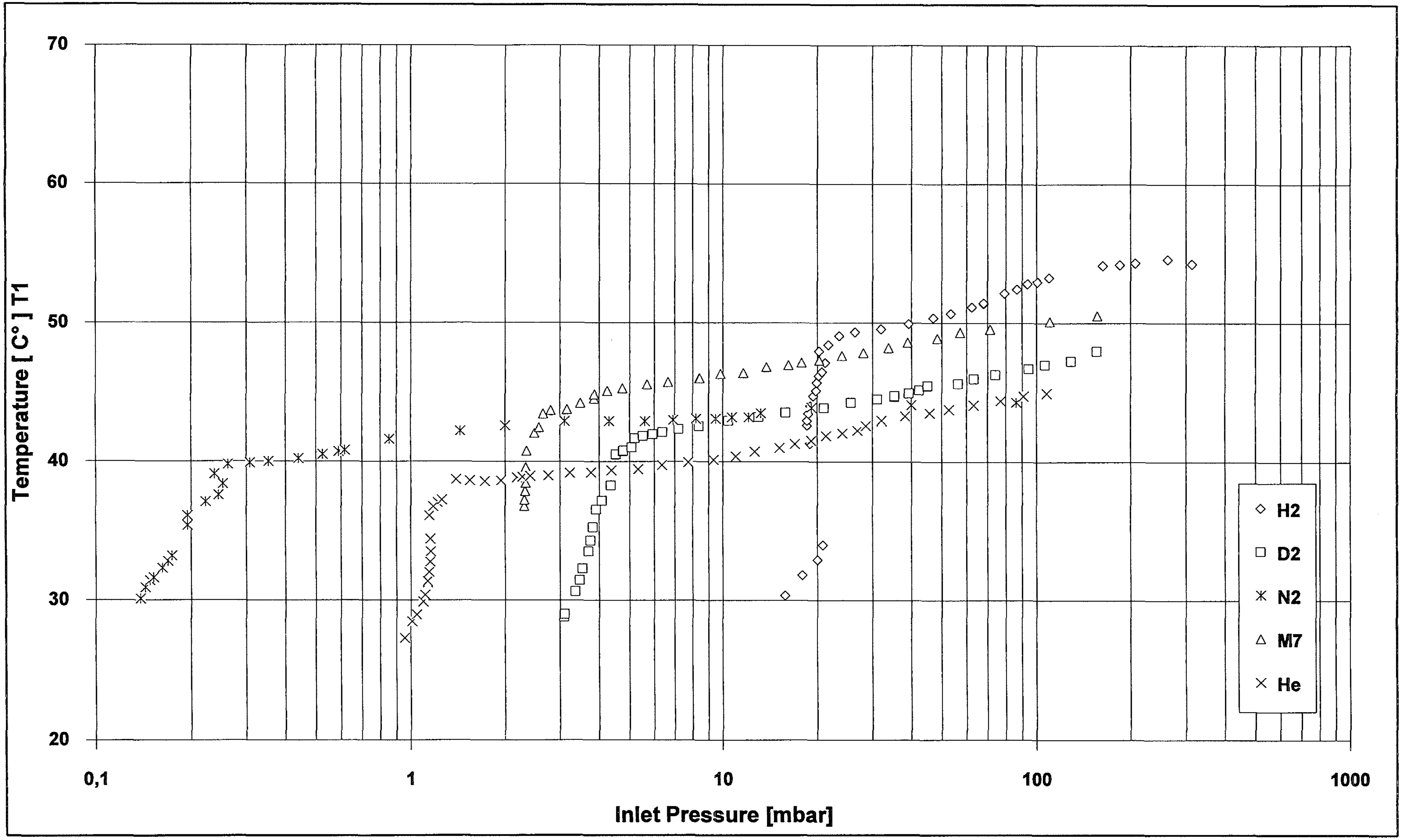


Fig.32: Oil temperature of NORMETEX 1300 pump for various gases at 600 mbar exhaust pressure

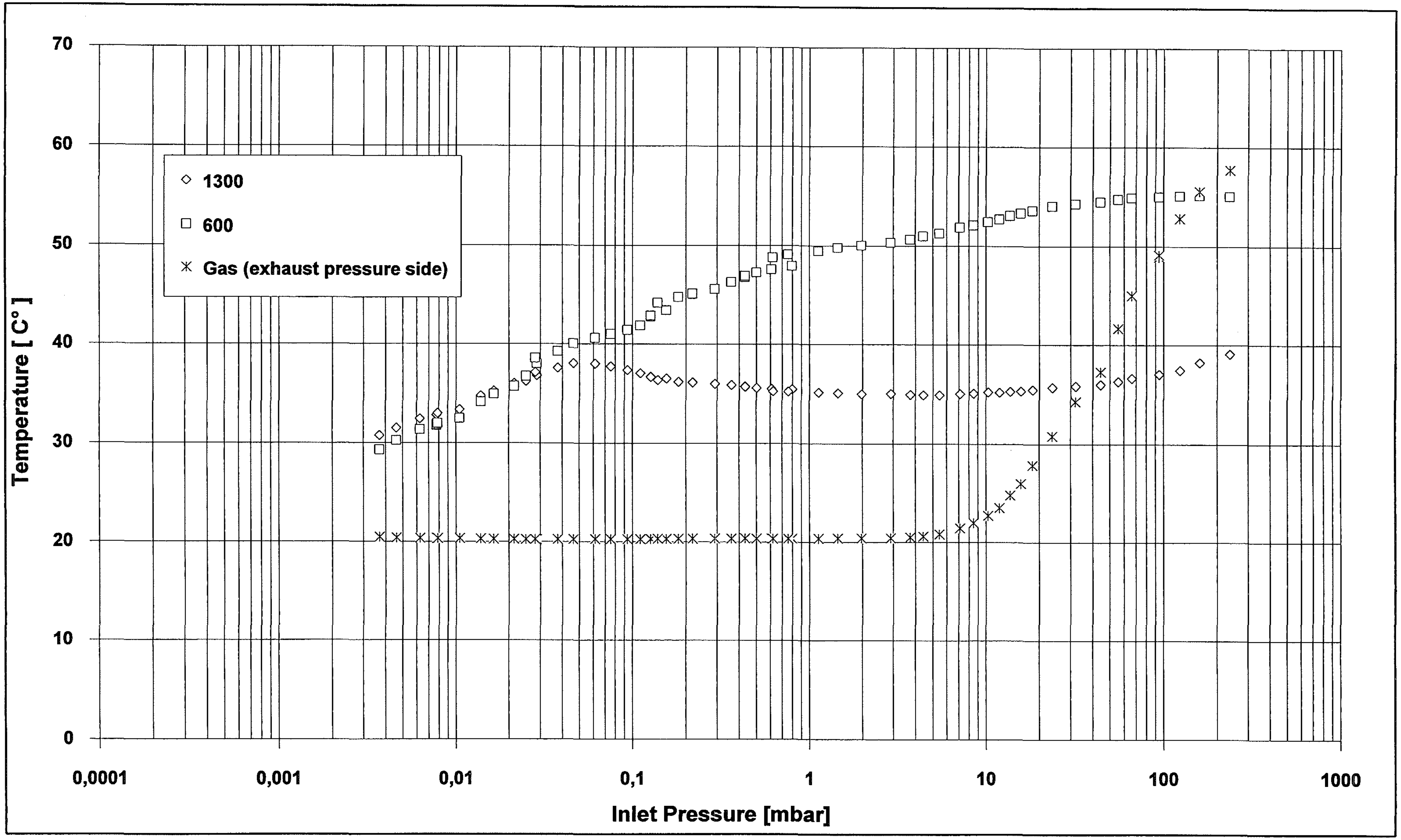


Fig.33: Oil temperature of NORMETEX 1300+600 pump train for M7 gas mixture at 1200 mbar exhaust pressure

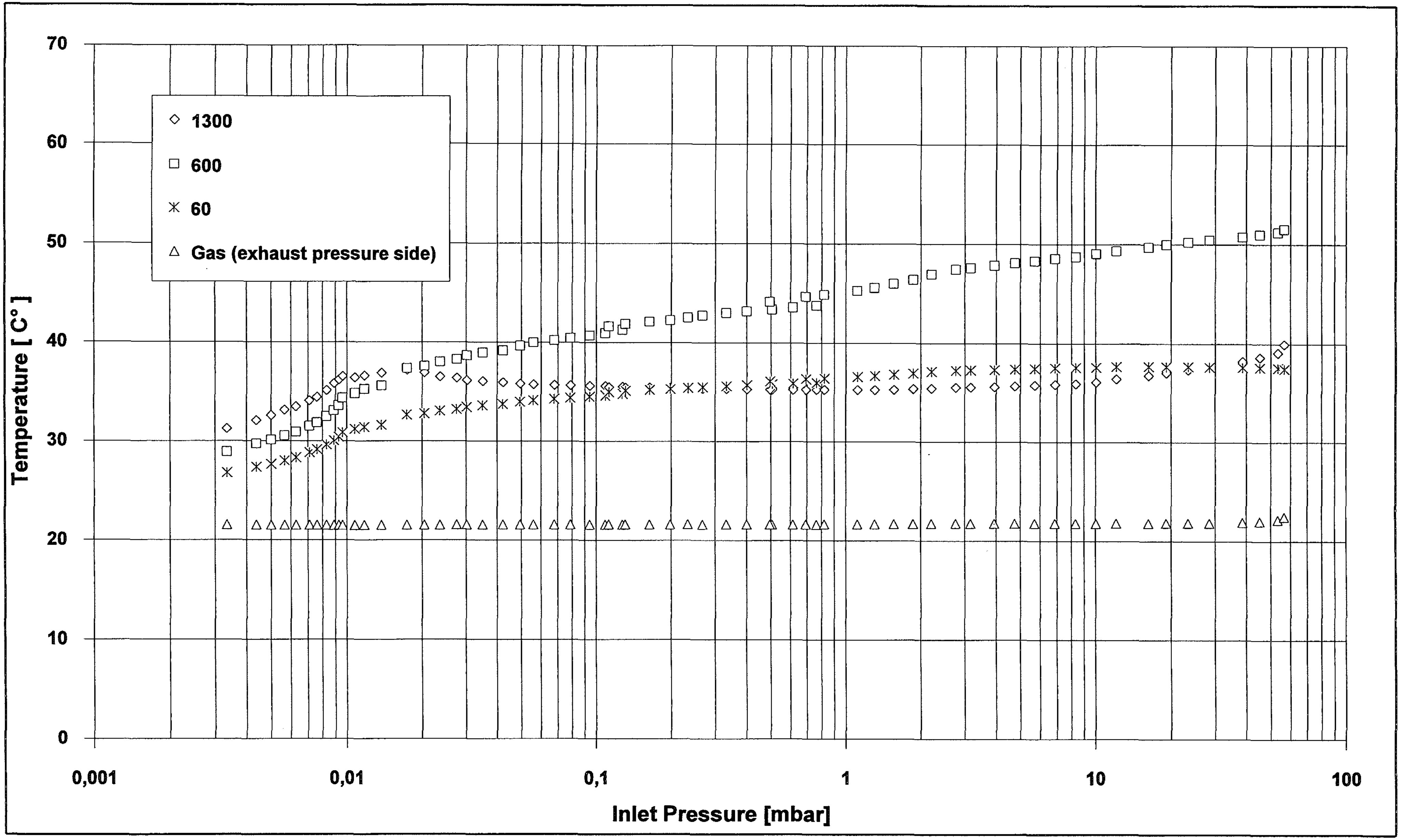


Fig.34: Oil temperature of NORMETEX 1300+600+60 pump tain for H2 gas at 1200 mbar exhaust pressure

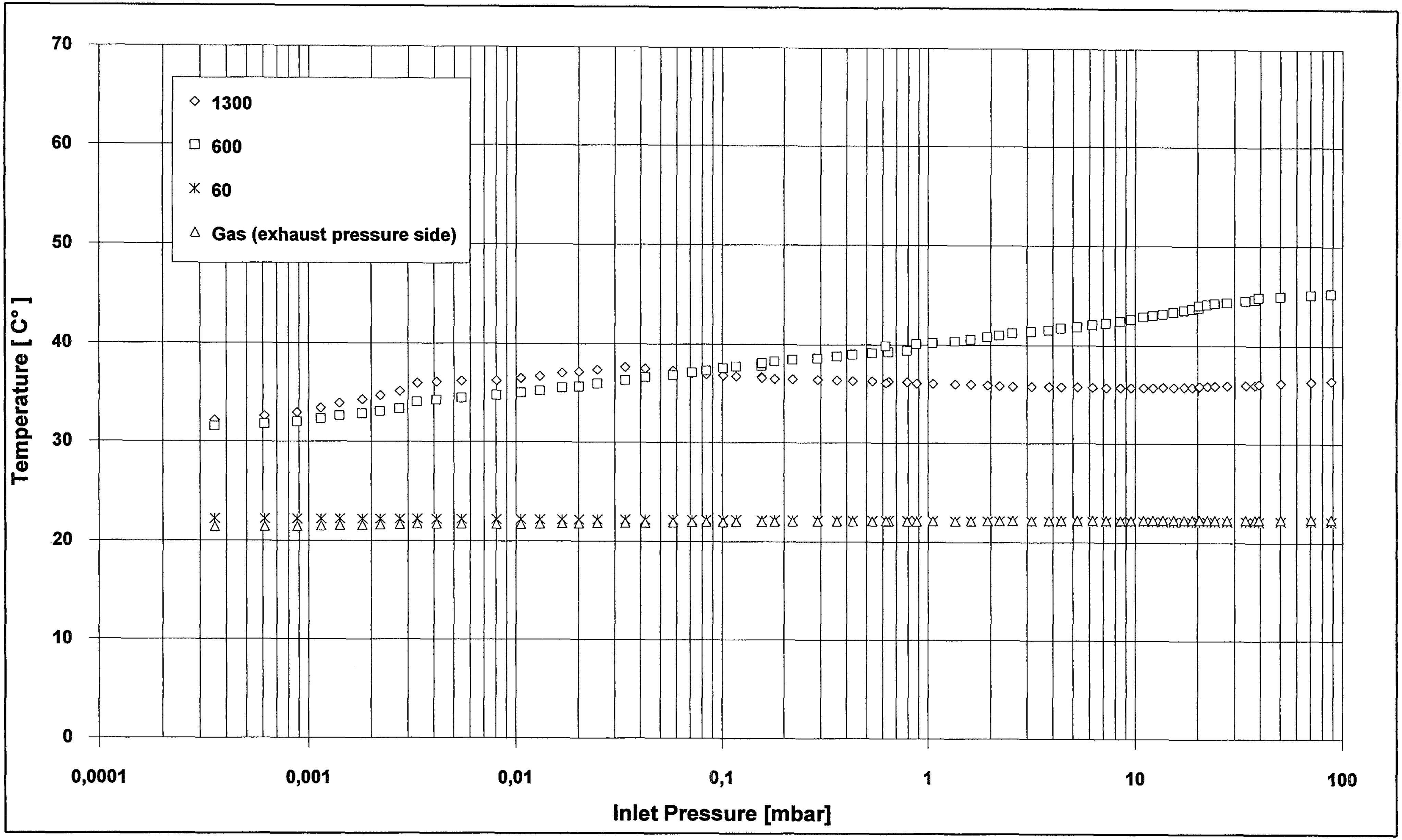


Fig.35: Oil temperature of NORMETEX 1300+600+60+METAL BELLOWS 6 pump train for M7 gas mixture at 1200 mbar exhaust pressure