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ABSTRACT

This paper will discuss the fundamentals of the Bosch rate of injection meter which has been the standard measurement tool for the last 25 years and a newly developed tool which uses the Zuech constant volume technique. A fundamental and experimental comparison is presented. Using a high pressure accumulator type injector, each of the injection systems produced almost identical injection rate shapes. The integrated values of these traces (injection quantity) were within a few percent of the physically measured quantities.

INTRODUCTION

Emission standards have led to the development of many new high pressure injection systems as a means of improving the combustion process in diesel engines. In addition to high injection pressures, the injection rate shape has also been shown to influence emissions [1,2]*. It is now essential to know the rate shape, as well as the injection pressure when attempting to optimize the engine operation. Therefore, accurate measurement of injection rate shapes using a rate of injection meter is an important part of injection system development. When evaluating a rate of injection meter, its 'ease of operation' and accuracy are the most important factors.

PRINCIPLES OF OPERATION

BOSCH RATE OF INJECTION METER - The Bosch type rate of injection meter records an injection rate by measuring the pressure wave that is produced by an injector when it injects into a length of compressible fluid (diesel fuel). Figure 1 shows a schematic of the Bosch type rate of injection meter as described in [3]. The meter consists of an injector mount, measuring tube, orifice, following tube and a check valve. The injector mount holds the injector so that the injector tip is positioned at the beginning of the measuring tube; it also holds the strain gages which are used to record the pressure waves. Between the measuring tube and the following tube is an orifice (usually a ball valve which enables quick orifice size adjustment). The size of the orifice determines what portion of the pressure wave is reflected and what portion enters the following tube. If the orifice is to large, the majority of the pressure wave will enter the following tube and a negative pressure wave will be reflected into the measuring tube. The inside diameter of the measuring tube determines the magnitude of the pressure waves while the length of the measuring tube affects the attenuation efficiency of the meter. A check valve located at the end of the following tube adjusts the back pressure on the enclosed volumes so that typical injection pressures can be used when testing an injector.

*Numbers in brackets indicate references at the end of the paper

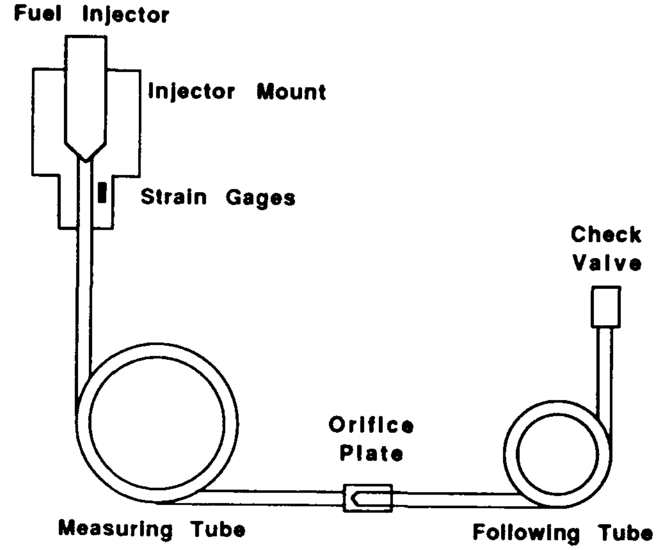

Fig. 1. Schematic of the Bosch rate of injection meter.

The concept of measuring the pressure wave to determine injection rates is based on the pressure-velocity equation valid for a single pressure wave in an instationary flow (eq. 1). It was derived from the hydraulic pulse theorem assuming one-dimensional motion.

$$P = a * \rho * u \qquad (1)$$

P = Pressure
a = Speed of Sound in Fluid
ρ = Density of Fluid
u = Flow Velocity

Combined with the continuity equation, the governing equation for the Bosch type rate of injection meter is derived (eq. 2) [3]

$$\frac{dq}{dt} = \frac{A}{a * \rho} * P \qquad (2)$$

where q is the volume of fuel and dq/dt is the volumetric flowrate. Therefore, integration of equation 2 produces q, the injected volume. The standard accuracy test is to compare this value to the measured volume being discharged by the check valve.

The validity of the one-dimensional wave motion assumption was investigated by Matsuoka, et al [4]. By measuring the pressure wave at two different positions along the length of the tube and comparing their shapes, they concluded the assumption was valid since the shapes of the curves were almost identical except for the slight time offset due to the different measurement positions.

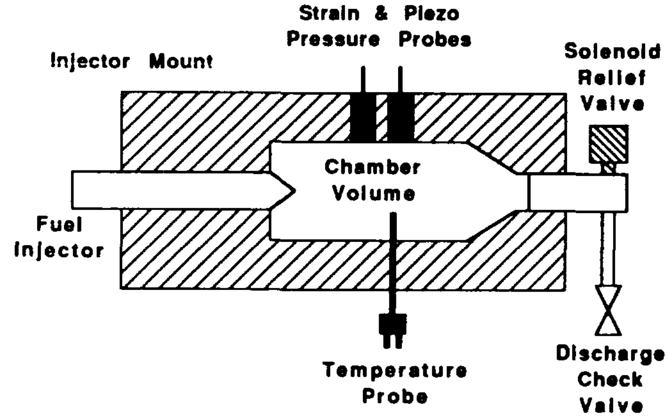

Fig. 2. Schematic of the Zuech rate of injection meter.

Although the integrated volume gives one form of accuracy, it does not verify that the recorded injection rate shape is accurate. Therefore, Bosch [3] and Matsuoka et al. [4] used rotating calibrates and discs respectively to verify injection rate shapes. Both concluded that this measuring tube method accurately recorded the magnitude and shape of the injection event.

ZUECH RATE OF INJECTION METER - The Zuech method [5] records the pressure of a constant volume chamber as an injection into the chamber occurs. As the mass of fuel in the chamber increases, the pressure of the fuel must increase. Through the bulk modulus of the fuel, the derivative of the constant volume chamber pressure produces the injection rate shape.

The Zuech rate of injection meter, shown schematically in figure 2, consists of an injection chamber equipped with a discharge and relief valve. The injection chamber is designed to hold the injector along with the temperature and pressure sensors. The relief (solenoid) valve is also connected to the chamber volume while the discharge (pressure regulating check) valve is in-line between the relief valve and a fuel reservoir. During the injection, the relief valve is closed; after the injection, it is opened and the chamber pressure is controlled by the discharge valve (then the relief valve is closed before the next injection). A thermocouple is used to monitor the chamber temperature while strain gage and piezo transducers are used to monitor the chamber pressure (strain gage records base pressure while piezo records dynamic changes in pressure).

The bulk modulus of the fuel is a function of pressure and temperature and generally determines the accuracy of the injection rate calibration. It is defined by equation (3)

$$K = V * \frac{dP}{dV} \qquad (3)$$

K = Bulk Modulus of the Fuel
V = Chamber Volume
P = Chamber Pressure

The bulk modulus is defined as the change in pressure due to a change in volume multiplied by the original volume; the bulk modulus is analogous to the modulus of elasticity for metals. Because the bulk modulus is important to the calibration, Takamura, et al. [5] included a motor driven reciprocating piston system in the recent design of their rate of injection meter. By monitoring the shaft encoder simultaneously with the chamber pressure and temperature, an accurate bulk modulus correlation was obtained.

The governing equation for the Zuech rate of injection meter is derived from the conservation of mass. Inserting the fuel bulk modulus produces the governing equation (eq. 4) [5].

$$\frac{dm}{dt} = \rho * \frac{V}{K} * \frac{dP}{dt} \qquad (4)$$

m = Mass of Fuel
ρ = Density of Fuel

Therefore, the mass injection rate is proportional to the fuel density, chamber volume, and the rate of chamber pressure rise and inversely proportional to the fuel bulk modulus. Therefore, the chamber pressure and fuel bulk modulus values must be known to a high degree of accuracy to produce 'smooth', accurate injection rates. Because the temperature in the chamber changes as a result of compression work during injection, a bulk modulus at the mean chamber temperature is used. Also, in the design of the chamber, its volume must be sized so that the chamber pressure rise will be within appropriate limits (1-3 MPa) for the desired volumetric injection range.

The most recently reported rate of injection meter based on the Zuech method is that of Takamura, et al. [4]. No references reporting the accuracy of the Zuech rate of injection meter were found. Although the total chamber pressure rise accurately predicts the injected quantity, it is the derivative of the chamber pressure that indicates the injection rate shape. Therefore, prediction of the injected quantity does not guarantee that the injection rate shape is correct.

EXPERIMENTAL DESCRIPTION

BOSCH RATE OF INJECTION METER - A schematic of the injector mount, the most critical part of the Bosch rate of injection meter, used for this comparison is shown in figure 3. The injector mount contains four 350 ohm strain gages arranged to measure hoop stress in a full-bridge arrangement. It also contains a piezo-electric access port so that the difference between strain gage and piezo-electric recorded rate shapes can be compared.

The length of the measuring tube is approximately 24.4 m (80 ft.) with an outside diameter is 9.53 mm (0.375 in.) and an inside diameter is 4.90 mm (0.193 in.). The orifice is provided by a ball valve which allows for size changes while observing the pressure waves on the oscilloscope. The following tube has an outside diameter of 6.35 mm (0.25 in.) and an inside diameter of 4.57 mm (0.18 in.) with a length of 6.1 m (20 ft.). The back pressure is controlled by a pressure-regulating check valve; the back pressure is indicated by a dial pressure gauge.

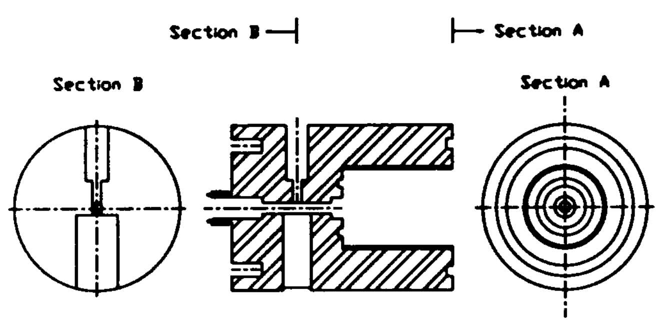

Fig. 3. Scaled Drawing of the Bosch injector mount (outermost diameter is 76.2 mm).

ZUECH RATE OF INJECTION METER - A schematic of the Zuech injector mount and chamber used in this experiment is shown in figure 4. The shape of the chamber is a cylinder with a conical contraction section on one end. The discharge valve was located at the center of the contraction section and the injector was located at the opposite end of the cylinder. The angle of the contraction was chosen so that any pressure waves would be deflected against the sides of the cylindrical

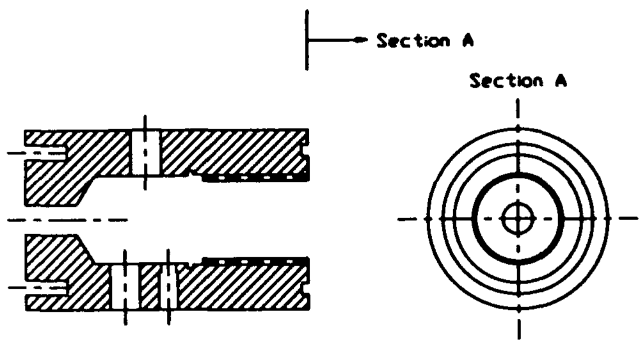

Fig. 4. Scaled drawing of the Zuech injector mount and chamber volume (outermost diameter is 76.2 mm).

section. The discharge valve is a 2-way, normally open high speed solenoid valve (response time of 0.6 ms) which was manufactured by SPI, Inc. The Kistler piezo-electric pressure transducer, type J open junction thermocouple, and full bridge 350 ohm strain gage transducer were located radially, approximately equidistant between the injector and discharge valve. The back pressure was controlled by a pressure-regulating check valve.

The volume of the chamber is 54.36 ml and was chosen for injection quantities between 50 and 150 mm^3. For these quantities, the chamber pressure will rise between 517 and 1379 kPa (75 to 200 psi).

CALIBRATION AND DATA ACQUISITION

INJECTION SYSTEM - The injection system used to acquire all experimental data was the BKM high pressure, accumulator type injection system. An extensive study of the injection system has been reported previously by Bower and Foster [7]. Typical peak injection pressures range between 100 and 140 MPa (14,500 and 20,300 psi) while injection quantities range between 45 and 100 mm^3. This injection system produces a very demanding test case for the rate of injection meters because it creates very flat injection rate shapes with very steep rising and falling edges. A 0.30 mm diameter, on axis, single hole nozzle with a orifice length to diameter ratio (L/d) of 4.0 was used. Needle closing occurred around 48 MPa (7000 psi). As listed in Table 1 , the injector was operated at two different injection frequencies, 500 and 1000 Hz and at two different peak injection pressures, 105 and 140 MPa (15,200 and 20,300 psi) for this experiment. The injection pressure were chosen to typify current high pressure injection systems. A single hole nozzle was used to minimize cycle to cycle injection variations due to slight differences in hole geometries associated with multi-hole nozzles.

TABLE 1

EXPERIMENTAL CONDITIONS

Case #	Maximum Injector Pressure	Injection Frequency
1	105 MPa	500 Hz
2	105 MPa	1000 Hz
3	140 MPa	500 Hz
4	140 MPa	1000 Hz

TEST FUEL - D-2 diesel fuel was used for all experimental conditions. Fuel density as a function of temperature was calibrated by simultaneously monitoring the volume of fuel in a graduated cylinder and the fuel temperature with a thermocouple. Fuel density was found to be linearly proportional to the fuel temperature and is calculated using equation 5.

$$\rho(T) = 847.5 - 0.9016 * T(^{o}C) \quad (5)$$

Other fuel properties include the kinetic viscosity (2.4 X 10^{-6} m^2/s) and the speed of sound in the fluid (1355 m/s @ 2.76 MPa). The speed of sound was calculated by dividing twice the length of the measuring tube (Bosch rate of injection meter) by the time between a pressure wave and its first reflection.

SYSTEM MODULUS (K) - Although K is usually defined as the bulk modulus of the fuel, system modulus is a more accurate definition since all calibrations are preformed in the Zuech chamber volume with no compensation for strain which occurs with internal pressure. As mentioned before, Takamura, et al. [6] used a motor driven reciprocating piston to acquire the calibration for the system modulus (K) as a function of temperature and pressure. In our experiment, we attempted to use a micrometer barrel as a means of accurately changing the chamber volume. Although the change in volume was known accurately, small temperature variation (0.1 °C) produced relatively large variances in the chamber pressure and therefore, unsatisfactory system modulus calibrations. As a second effort, the injection system parameters were locked on a chosen setting and the injected mass was then measured. Operating this injector under these conditions in the Zuech rate of injection meter at different chamber baseline pressures and temperatures, the change in the chamber pressure could be used to calculate a system modulus for a given temperature and pressure knowing the injected mass (injected mass was also measured during calibration to ensure consistent delivery quantities) using equation 3 ($dV = dm/p(T)$). Using 25 experimental values, a correlation for the system modulus versus temperature and pressure was calculated. The system modulus was found to be a linear function of temperature and a nonlinear function of pressure. The correlation is shown in equation 6.

$$K = 611 + 305\,P - 3.13\,T - 27.6\,P^2 \qquad (6)$$

K = System Modulus
P = Mean Injection Pressure
T = Mean Injection Temperature

DATA ACQUISITION - All data was acquired using a Tektronix model 11401 oscilloscope. As a means of 'smoothing' experimental traces, all traces were ensemble averaged (performed by the oscilloscope) for 16 consecutive injections. Once captured, they were downloaded to an IBM compatible computer and stored in a data file. A spreadsheet program was then used to convert voltage values into their appropriate units which were then graphed.

In order to 'smooth' the derivative of the Zuech chamber pressure so that the rate shape contained an acceptable noise level, the chamber pressure traces were center averaged with a 9 point smoothing technique. Instead of filtering the original signal with a lowpass filter, center averaging was used as a means of minimizing the phase shift imparted on the injection rate shape.

Strain gage signals were amplified using an Omega OM3-WBS-10 amplifier (20 kHz bandwidth). A Kistler model 5004 charge amplifier was used to amplify all piezo-electric signals.

EXPERIMENTAL RESULTS

BOSCH RATE OF INJECTION METER - STRAIN vs. PIEZO - Because a piezo-electric pressure transducer requires direct contact with the pressurized medium, the piezo-electric transducer used on Bosch rate of injection meters have been questioned since they break the continuity of the measuring tube wall. Therefore, a piezo-electric pressure transducer was located 55 mm beyond a strain gage measurement section on a Bosch rate of injection meter. As shown in figure 5, the piezo rate shape is almost identical to the strain gage rate shape. It appears as if the piezo access port does not noticeably alter the shape of the pressure wave. This result also lends credibility to the assumption of a one-dimensional pressure wave which was used in the derivation of the Bosch governing equations. After obtaining this result, a new injector mount was manufactured where the piezo-electric and strain gage measurement section were located at the same axial distance from the injector mount (figure 3).

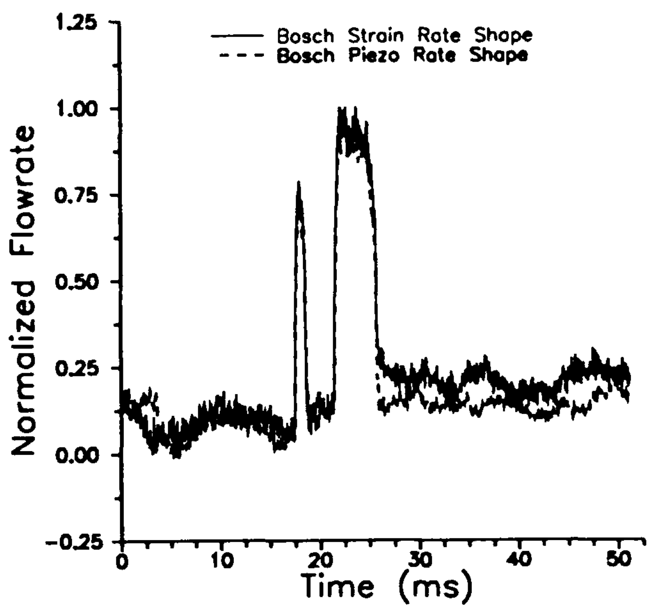

Fig. 5. Comparison of a normalized strain gage and piezo-electric signal from a Bosch rate of injection meter when the piezo transducer was located 55 mm beyond the strain gage measurement section.

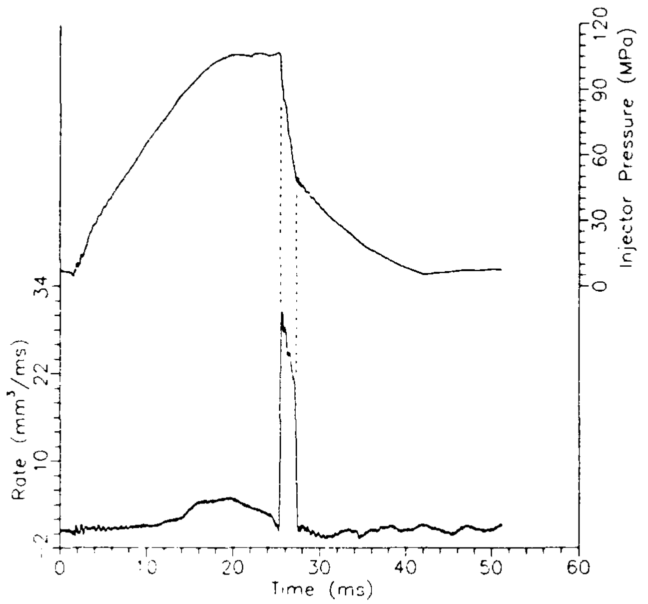

Fig. 6. Simultaneous traces recorded using the Bosch rate of injection meter. Traces include injector accumulator pressure and injection rate shape. Vertical lines indicate the beginning and end of injection.

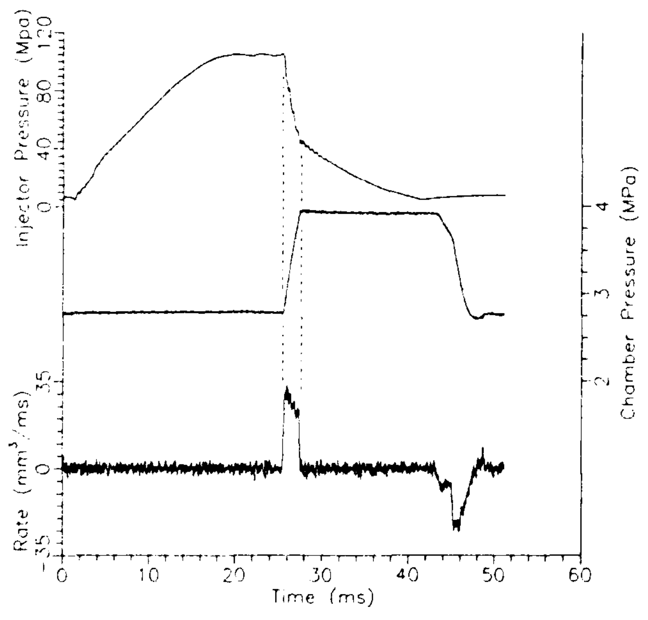

Fig. 7. Simultaneous traces recorded using the Zuech rate of injection meter. Traces include injector accumulator pressure, Zuech chamber pressure, and injection rate shape (calculated from the derivative of the chamber pressure). Vertical lines indicate the beginning and end of injection.

INJECTION RATE SHAPES - Figures 6 and 7 show a set of complete traces that were recorded using the Bosch and Zuech rate of injection meters respectively. From Figure 6, the injection rate shape is 'smooth' while the reflected pressure waves create a 'rolling' baseline measuring tube pressure. The accumulator (injector) pressure trace verifies that the injection rate shape begins and ends at the correct time. The discontinuities in the accumulator pressure trace indicate when the injection starts and stops; the first discontinuity is at the top of the smooth rising part of the trace and the second occurs where noise (from needle closing) occurs in the negative slope region. Figure 7 shows both the accumulator pressure trace and the injection rate shape in addition to the chamber pressure which were recorded with the Zuech rate of injection meter. The injection rate shape appears 'noisy' as the accumulator and chamber pressure traces appear smooth. The increase in the chamber pressure trace is due to the injection of fuel while the decrease is due to the venting of the chamber through the relief and discharge valves.

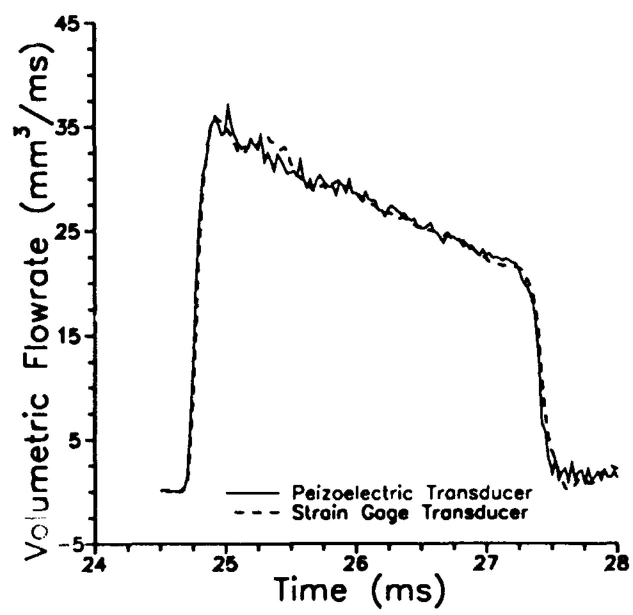

Fig. 8. Piezo-electric and strain gage recorded rate shapes using a Bosch rate of injection meter for experimental case 3 (peak injector pressure of 140 MPa and injection frequency of 500 Hz).

TABLE 2

INJECTION VOLUME - BOSCH RATE OF INJECTION METER

Case #	Measured Volume	Strain Volume	Strain % Diff.	Piezo Volume	Piezo % Diff.
1	46.5	46.0	1.09	46.1	0.86
2	59.8	56.3	5.85	55.8	6.69
3	74.9	73.9	1.34	74.1	1.07
4	89.0	84.7	4.83	86.2	3.15

TABLE 3

INJECTION VOLUME - ZUECH RATE OF INJECTION METER

Case #	Measured Volume	Strain Volume	Strain % Diff.	Piezo Volume	Piezo % Diff.
1	47.8	49.0	2.51	47.8	0.00
2	62.3	62.3	0.00	60.8	2.41
3	75.4	75.4	0.26	73.6	2.65
4	89.8	89.6	0.22	87.3	2.78

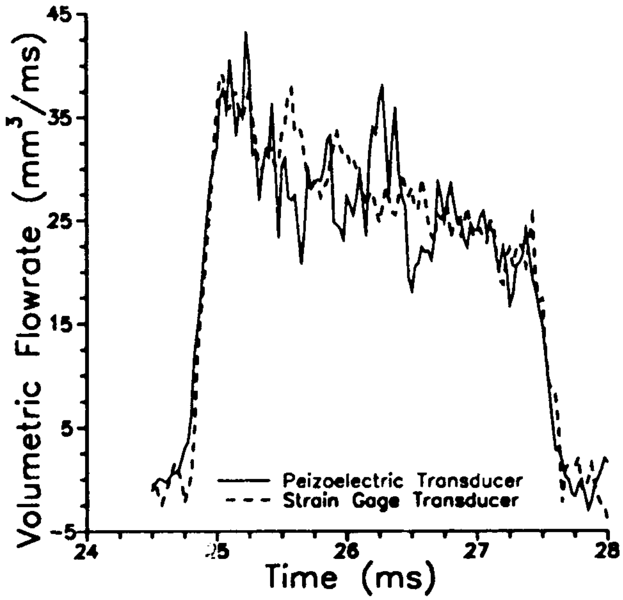

Fig. 9. Piezo-electric and strain gage recorded rate shapes using a Zuech rate of injection meter for experimental case 3 (peak injector pressure of 140 MPa and injection frequency of 500 Hz).

Injection rate shapes for experimental condition 3 (Table 1) is shown in figure 8 for the Bosch rate of injection meter and figure 9 for the Zuech rate of injection meter. At first glance, the Bosch rate trace seems much 'smoother' than the Zuech rate trace. Figures 8 and 9 indicate that properly designed strain gage arrangements (full bridge) can measure dynamic pressure changes as accurately as piezo-electric transducer without the associated drifting problem. For the experimental conditions listed in Table 1, injection volumes were integrated from the rate traces for the Bosch system while injected volumes were calculated using the total pressure rise in the chamber volume for the Zuech system. These values are shown in Table 2 and Table 3 respectively where they are compared to measured volumes.

From Table 2 and 3, it is observed that Zuech rate of injection meter predicts injected volumes more accurately. From Table 2, the Bosch rate of injection meter predicts the injected volume more accurately at lower injection frequencies. Because the pressure waves are reflected back and forth through the measuring tube until they are attenuated, the higher injection frequencies have larger reflected waves superimposed on the injection rate shape. Changing the length and diameter of the measuring tube will change the attenuation

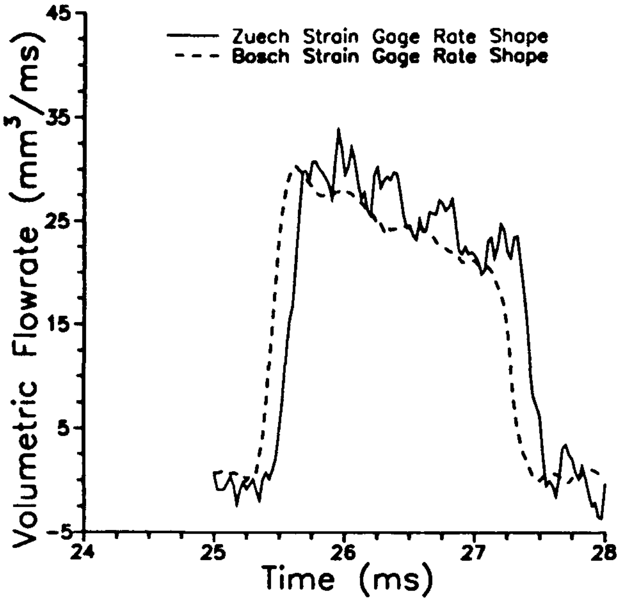

Fig. 10. A comparison of the strain gage transducer's injection rate shapes from the Bosch and Zuech rate of injection meters for experimental case 1 (peak injector pressure of 105 MPa and injection frequency of 500 Hz).

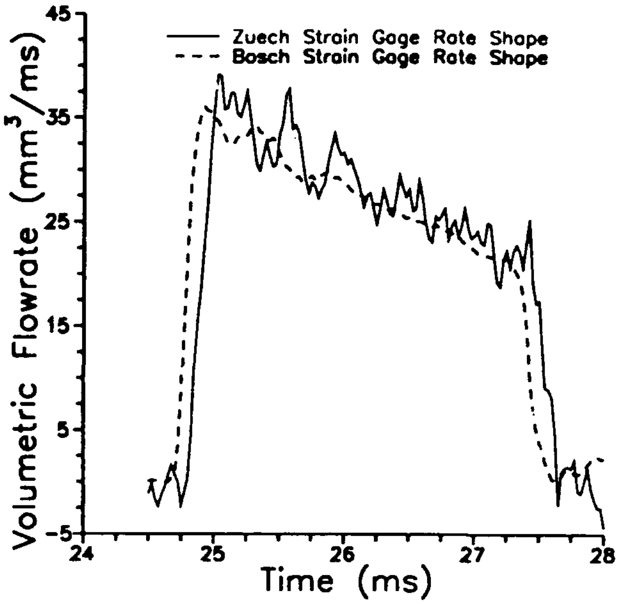

Fig. 12. A comparison of the strain gage transducer's injection rate shapes from the Bosch and Zuech rate of injection meters for experimental case 3 (peak injector pressure of 140 MPa and injection frequency of 500 Hz).

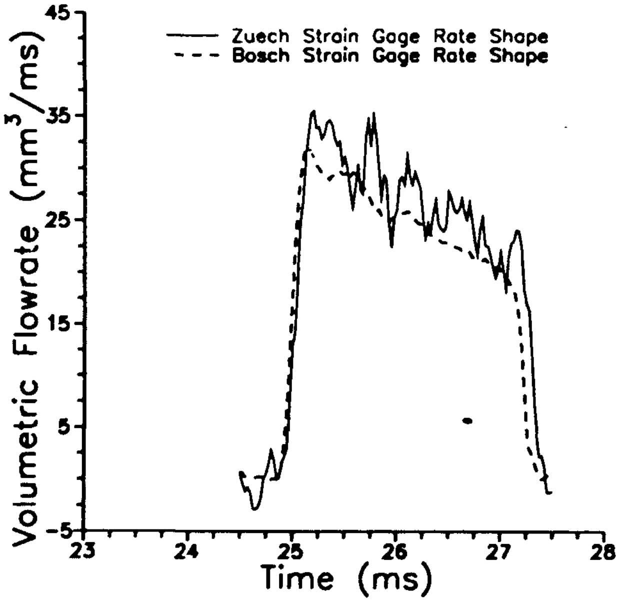

Fig. 11. A comparison of the strain gage transducer's injection rate shapes from the Bosch and Zuech rate of injection meters for experimental case 2 (peak injector pressure of 105 MPa and injection frequency of 1000 Hz).

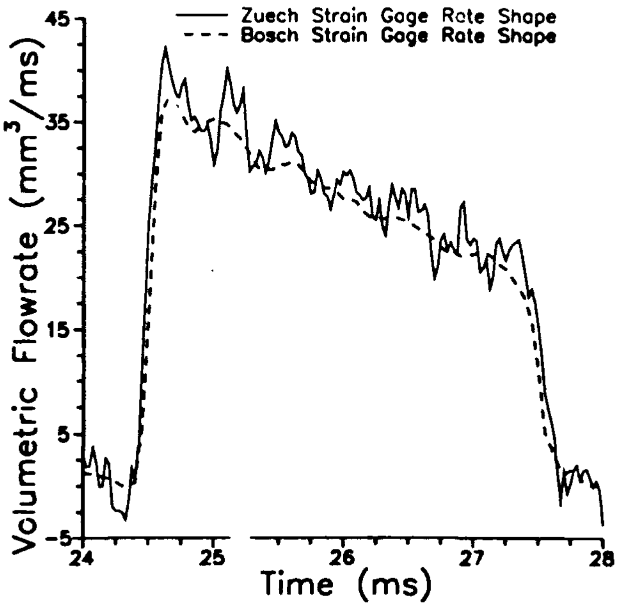

Fig. 13. A comparison of the strain gage transducer's injection rate shapes from the Bosch and Zuech rate of injection meters for experimental case 4 (peak injector pressure of 140 MPa and injection frequency of 1000 Hz)

efficiency of the Bosch rate of injection meter. As injection rates increase (higher injection pressures) larger pressure waves are created in the measuring tube and greater attenuation will be needed to keep a constant baseline pressure for the injection rate shape. This is a disadvantage for the Bosch system while it does not occur in the Zuech method.

Direct comparison of the Bosch and Zuech rate shapes are shown in figures 10-13 for experimental cases 1-4 (see Table 1) respectively. A slight shift in the Zuech rate shapes can be seen due to the 9 point center averaging technique. Overall, both system predict the same type of injection rate shape with the Bosch system producing a very 'smooth' rate shape while the Zuech system produces a 'noisy' signal as a result of the derivative.

SUMMARY

* Both systems predict the same magnitude and shape of injection rate.

* The Bosch method requires no timing between the injection system and the rate of injection meter while the Zuech method requires a phasing between the injection event and the relief valve operation.

* The signal from Bosch system is directly proportional to the injection rate shape while a derivative is required for the Zuech system.

* The injected volume is calculated from an equation for the Zuech method while numerical integration is required for the Bosch method.

* The Zuech method is more accurate at predicting injected volumes while the Bosch method produces a much 'smoother' injection rate shape.

* The Bosch rate of injection meter measures a one-dimensional pressure wave through a long measuring tube to predict the injection rate shape while the Zuech rate of injection meter uses the derivative of a chamber pressure history to predict injection rate shapes.

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SYMBOLS

P - Pressure
a - Speed of sound in fluid
ρ - Density of fluid
u - Flow velocity
A - Cross sectional area
q - Injected volume
V - Volume
K - Bulk modulus of fuel
t - Time
T - Temperature