erating sulfuric acid process with a new process that has similar economics.

R&D guidelines

The ideal solid-catalyst alkylation process would have the following characteristics, which can serve as a goal and benchmark for research and development and competitive evaluation:

- The new process should be simple and easy to operate. A fixed-bed reactor is preferable to a slurry reactor in this respect.
- A new process that is intended to ameliorate the safety and environmental problems of current processes should not introduce new problems of this type.
- In a retrofit situation, the new process should utilize existing equipment as much as possible, and the new equipment should fit in the available space.
- The overall process should have turnaround times long enough to match those of the FCC units. This calls for standby reactors and continuous (or nearly continuous) catalyst regeneration.
- The process should not require esoteric feedstock cleanup technology that would increase costs.
- The yield and quality of gasoline should be better than that of the incumbent processes.
- The catalyst should be selective with all C_3 to C_5 olefins in the feed.
- The process should accept feedstocks of I/O ratio less than or equal to that used in sulfuric acid processes.
- The process should operate at or above ambient temperature.
- The product separation system should be more economical and energy-efficient than the traditional DIB column.
- The process should be more economical, environmentally compatible, and safer than sulfuric acid processes.

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Multiple-correlations improve well pressure-loss calculations

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Different correlations applied to each segment of a well bore provide better pressure-loss estimates than a single-correlation for the entire well.

Four widely used multiphase-flow correlations have been defined on superficial velocities maps. Generally, a Duns and Ros correlation is best for mist flow regime (high gas velocity), but high water cut reduces its accuracy dramatically. Both Hagedorn and Brown, and Beggs and Brill correlations can give good results in case of high water cut.

No correlation can be satisfactorily applied in the transition region from bubble to slug regimes.

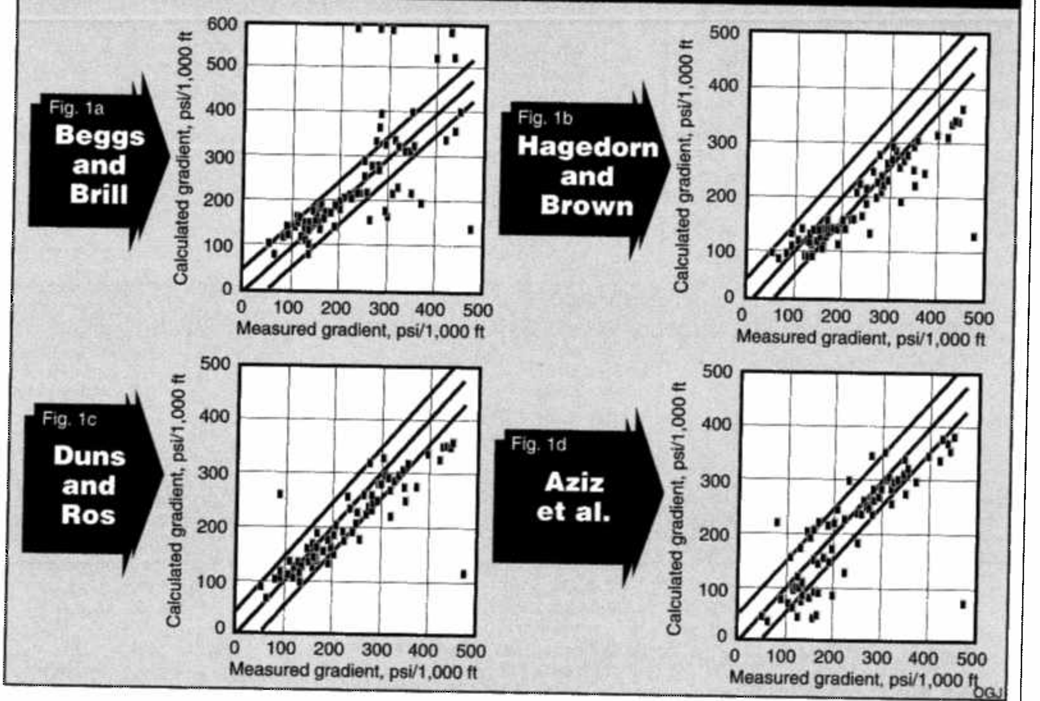
To develop and verify this approach, actual field multiphase-flow data points were obtained from different naturally flowing and gas lifted oil wells in four different Gulf of Suez fields.

After testing various pressure-volume-temperature (PVT) correlations against actual PVT data, the best correlations for different PVT properties for each particular field were identified.

These best correlations, subsequently were used to calculate multiphase-flow pressure drop. The error analysis of different multiphase-flow correlations has been related to the in situ flowing conditions. The applicable ranges of the most widely used correlations have been defined on two-dimensional superficial velocity maps.

Fig. 1

FIELD A PRESSURE GRADIENTS*



Multiphase flow

Multiphase flow in the petroleum industry occurs nearly in each component of the production system, such as production tubing, surface flow lines, risers, gathering lines, and pipelines.

Two approaches for predicting pressure losses in multiphase flow in pipes are: the empirical and mechanistic (semianalytical).

The empirical approach correlates pressure losses empirically with the most important parameters without explaining the cause of the phenomenon. The mechanistic approach, which is more recent, attempts to describe the phenomenon analytically with physics. This article is limited to the empirical approach.

Many multiphase-flow correlations[1-5] and comparative evaluation studies[6-10] for these correlations have been developed and conducted over the years. Preliminary analysis shows that there are large errors associated with the current methods of pressure-loss prediction that can not be related to a certain range of a single parameter.

These errors may be attributed to the inaccuracy of PVT correlations and/or the use of a single multiphase-flow correlation in the calculations of pressure losses

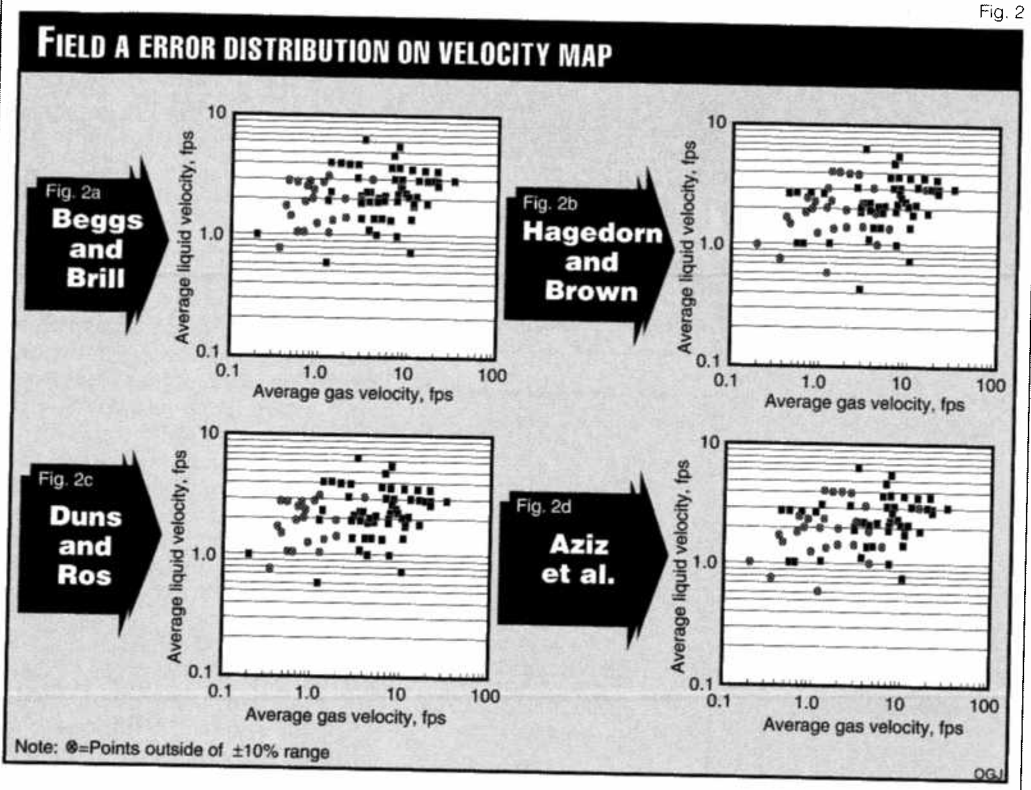


Fig. 2

FIELD A ERROR DISTRIBUTION ON VELOCITY MAP

Note: ⊗=Points outside of ±10% range

along the flow path from the top to the bottom of the well.

PVT properties

Because PVT properties may be a source of errors in multiphase-flow calculations, it is always desirable to select the most appropriate PVT correlations for the concerned fluids.

In this study, a PVT comparative study for the Gulf of Suez crudes was carried out. Preliminary validation of the reported laboratory results was conducted by mass balance calculations. The reported differential PVT data were corrected to flash data to simulate gas liberation in the production tubing.

Various PVT correlations have been tested against actual PVT data. Published PVT correlations[11-27] are used in this study and the best correlations for all PVT properties have been determined.[28] These identified best correlations for each field have been adopted in the subsequent multiphase pressure-loss calculations.

Data base construction

Multiphase-flow data were collected from four different fields in the Gulf of Suez. These data include naturally flowing and gas-lifted wells. A data base system was constructed from the collected field data that includes physical dimensions for each measurement point such as diameter and angle of well bore inclination, measured flowing pressure and temperature surveys, and flowing rates of gas, oil, and water.

The total number of data points was 731. Table 1 shows the ranges of multiphase data included in the data base.

Table 1

RANGES OF MULTIPHASE DATA

	Minimum	Maximum
Liquid rate, st-tk b/d	405	8,521
Gas/liquid ratio (GLR), scf/st-tk bbl	35	4,530
Water cut, %	0	92
Angle	0	62
Inside Diameter, in	2.992	6.18
Average in situ superficial liquid velocity, fps	0.5	13.43
Average in situ superficial gas velocity, fps	0.01	124.2

Programming correlations

Multiphase-flow correlations can be categorized into three categories according to their theoretical basis.[5]

Category 1 correlations neglect both the slippage effect and flow regimes. Category 2 correlations respect the slippage phenomenon, and do not recognize the flow regimes. Category 3 correlations recognize the flow regimes and slippage phenomenon.

Theoretically, Category 1 and 3 correlations are more suitable for multiphase calculations because they account for the slippage and viscous effects.

Previous evaluation studies[7 8 29] on some Gulf of Suez fields suggest that the following correlations are the most suitable correlations:

1. Duns and Ros correlation (Category 3)
2. Modified Hagedorn and Brown (Category 2)
3. Govier, Aziz, and Fogarasi correlation (Category 3)
4. Modified Beggs and Brill correlation (Category 3).

Therefore, these four correlations were selected for further evaluation. These correlations are programmed in such a way that the calculations can be made from the top to the bottom or from the bottom to the top of a well.

The program calculates the measured gradient and the average in situ superficial gas and superficial liquid velocities at each multiphase data point. It also calculates the pressure drop and the gradient at each multiphase data point for each correlation. The results are also added to the data base.

Multiphase-flow correlations

Fig. 1 presents the calculated gradient-vs.-measured gradient for Field A data points. The higher and lower lines represent +10% and −10% of the maximum measured gradient as an acceptable accuracy range. Notice that there are a number of points out of the accuracy range for each correlation.

Table 2 gives a list of the data points that are out of the acceptable accuracy range for Beggs and Brill correlation in Field A. It is important to notice that there is no range for liquid rate, gas/liquid ratio, or water cut for these points. Instead, there are low, medium, and high values for each parameter. This is also valid for the other correlations.

This means that these high error points cannot be restricted to a certain range of a single parameter. Based on this, these high error points are studied at in situ flowing conditions (not as related to single parameters). Therefore, points are located on the flow map of superficial liquid velocity-vs.-gas velocity of Field A.

Fig. 2 shows that all the correlations give poor results in one zone on the map, between superficial gas velocity of about 0.1-2 fps. Hagedorn and Brown correlation gives worse results in a wider zone (Fig. 2b) while Duns and

Aziz correlations give somewhat better results, lower number of high error points.

An investigation of the high error points of each correlation on Fields B, C, and D has confirmed that these points lie within the same area on the map regardless of the field or the correlation.[28]

These results emphasize the need for a reliable and objective approach for studying the applicability range of each correlation under in situ flowing conditions. Therefore, a flow regime map that combines the effects of liquid rate, gas/liquid ratio, diameter, pressure, temperature, and PVT properties would be more reliable in illustrating the combined effect of these different parameters.

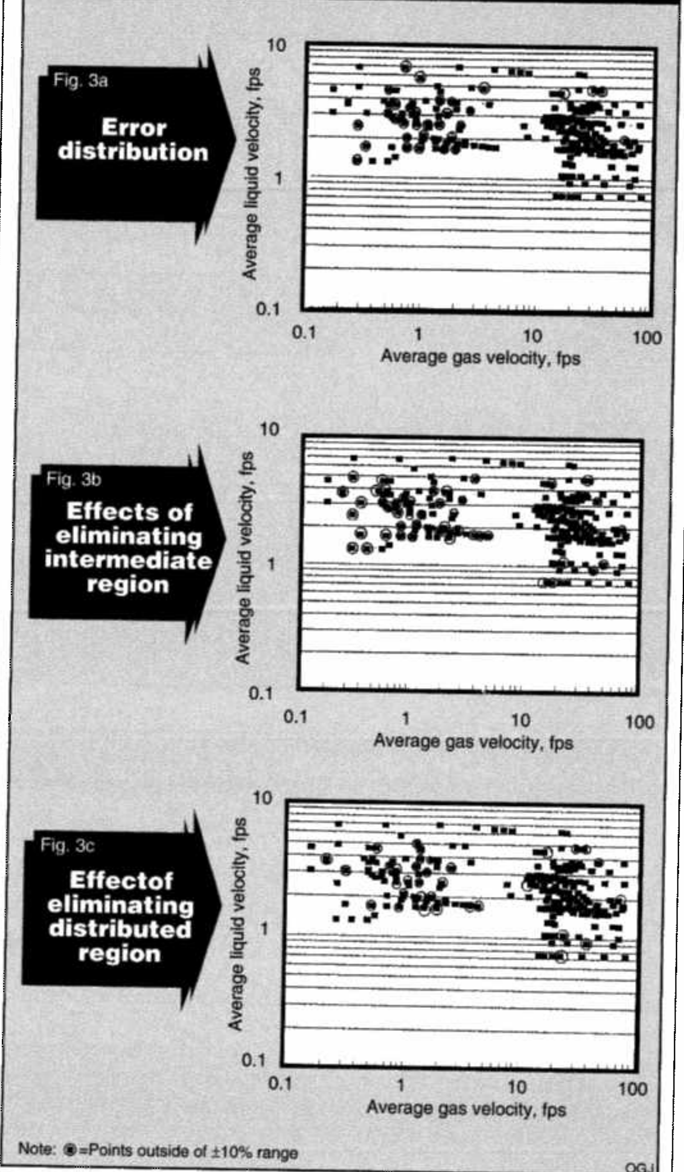
The high concentration of low accuracy points in one area on the flow pattern map can be explained by the fact that there is no sharp, well-defined boundary between the bubble and slug flow regimes. These points can neither be described as bubble nor as slug flow regime points, rather they lie in the transition zone between bubble and slug flow regimes.

According to this explanation, the holdup equations of both bubble and slug regimes for all correlations cannot correlate or describe these transitional points. This explanation is supported by the following observations as applied to Field C:

- The flow regimes of high error points of Field C are checked using the Beggs and Brill correlation because it is a Category 3 correlation (Fig. 3a). It has been found that the flow regime of these points is either distributed or intermittent, according to Beggs and Brill.
- Elimination of the intermittent flow regime from the correlation, by forcing the program to use the distributed regime instead, increases the number of high error points from 92 to 111. Most of these points were originally classified as intermittent points. Fig. 3b gives the distribution of the high error points when the intermittent regime is eliminated.

Fig. 3

FIELD C BEGGS AND BRILL CORRELATION



Note: ●=Points outside of ±10% range

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- Elimination of the distributed flow regime from the correlation, by forcing the program to use the intermittent regime equations instead, decreases the number of high error points from 92 to 60. This is true especially for the points that were originally classified as distributed regime points. Fig. 3c gives the distribution of high error points with the elimination of the distributed regime from the correlation. This means that the number and distribution of the high error points are sensitive to the position of the boundary between the distributed and intermittent regimes.

Also concluded is that the intermittent regime equations describe better some of the points that were originally described as distributed in the correlation, while the distributed regime equations fail to describe the intermittent points.

This gives rise to the possibility of the presence of a transition zone between the distributed and intermittent regimes. In addition, a modified equation for the intermittent flow regime equation may be developed to describe this transition zone.

An alternative to determining flow regimes at the high error points at the actual angle of inclination is to have an inclined flow pattern map. (Notice that the Beggs and Brill flow pattern map gives the flow regime that would exist if the pipe were horizontal.)

The Barnea, et al., flow pattern map[30] for inclined flow was programmed from which the flow regime at the high error points was determined. Also found was that the actual flow regimes at these points are either distributed bubble or intermittent. This confirms the conclusion that these points are transitional points between the bubble and slug regimes.

Velocity maps

On the superficial velocity maps of Fields A, B, C, and D, the different multiphase data points overlap and coincide on the same map. Also, the zonation of the low accuracy points would not be unique on the same map and instead there are various possible geometrical boundaries that may define this area.

Gridding of the superficial velocity map can avoid the overlap between the different points and to help in zoning any area objectively.

The error of any correlation at each measurement point on the map is defined as:

$$\epsilon = (dp/dl)_{calculated} - (dp/dl)_{measured}$$

The error at each measurement point on the map is calculated for each correlation. The map is gridded into 40 x 40 rectangles. The grids are applied between the minimum and maximum average gas and liquid velocities of the field.

The value of the error at each grid is determined by interpolation between the errors of the real surrounding points. Thus an error surface is established for each correlation on the gridded map of the field.

An accuracy limit of 10% of the maximum measured gradient of the field has been

Fig. 4

FIELD A APPLICATION RANGE

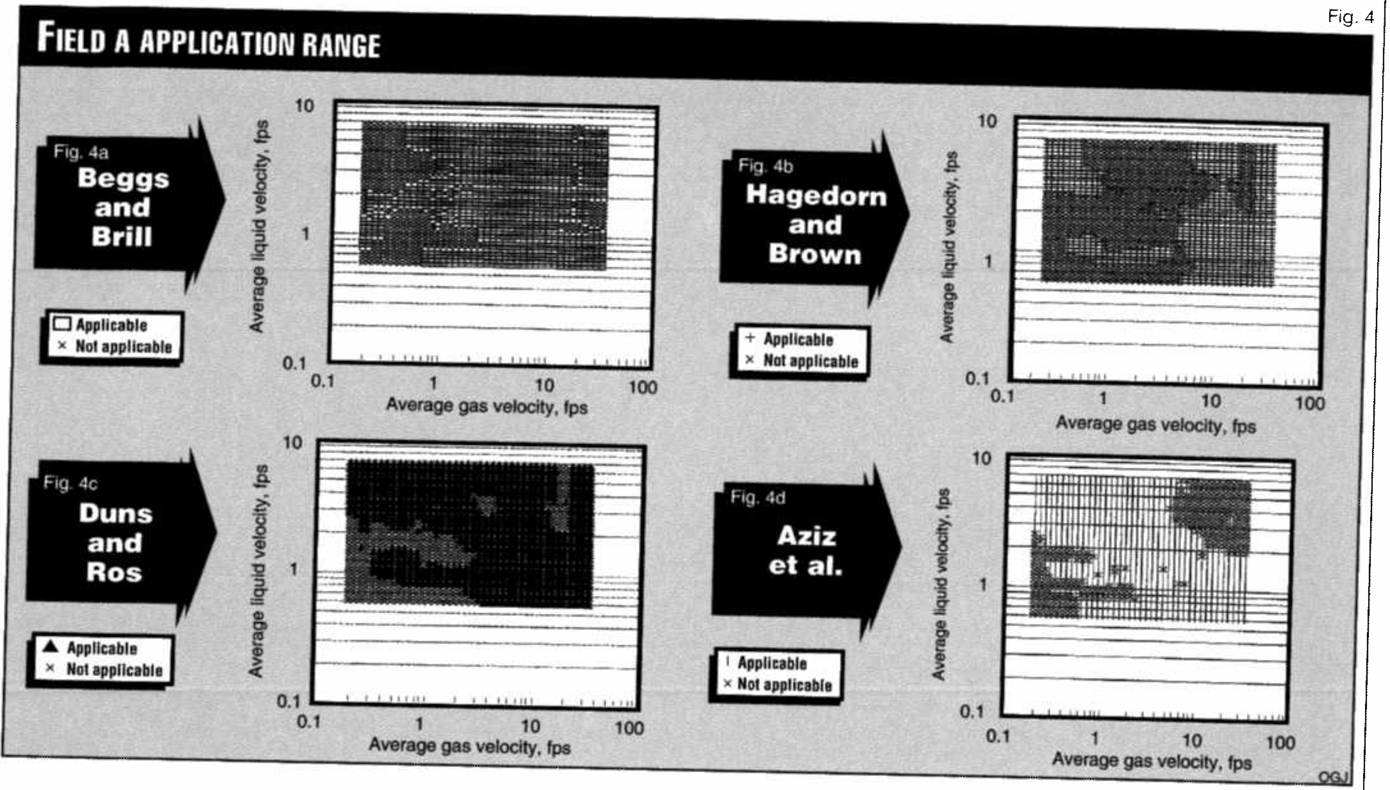


Table 2

POINTS OUT OF ± 10% ACCURACY LIMITS*

Liquid flow (Q_L), st-tk b/d	Gas/ liquid ratio, scf/st-tk bbl	Water cut	Average liquid velocity, fps	Average gas velocity, fps	Gradient, psi/1,000 ft. Caclulated	Gradient, psi/1,000 ft. Measured
2,043	145	0.75	2.79	1.09	184.82	292.98
2,043	145	0.75	2.8	0.76	161.8	261.84
2,043	145	0.75	2.81	0.56	169.99	298.25
2,043	145	0.75	2.83	0.45	221.1	309.49
2,270	200	0.75	3.11	3.92	404.28	347.59
2,270	200	0.75	3.12	1.25	526.7	396.14
2,270	200	0.75	1.93	0.69	526.69	435.04
2,444	413	0.25	2	1.93	294.48	247.47
2,444	413	0.25	2.05	1.23	398.36	281.56
2,444	413	0.25	2.08	0.82	370.02	279.28
2,444	413	0.25	1.49	0.47	338.24	272.88
1,394	602	0.09	1.9	16.38	107.79	49.95
2,600	762	0	2.4	3.4	85.24	133.57
3,756	2,236	0.45	2.98	21.67	147.31	89.11
3,756	2,236	0.45	3.03	18.23	144.34	473.72
3,756	2,236	0.45	2.17	9.86	167.88	108.84
2,972	294	0.53	2.44	0.88	342.11	418.75
2,972	294	0.53	1.73	0.42	361.65	440
1,330	519	0.65	1.06	1.28	594.58	228.84
1,330	337	0.65	1.06	0.65	591.18	274.99
1,330	337	0.65	1.06	0.56	588.66	302.01
1,330	337	0.65	0.76	0.36	584.77	427.76
2,770	4,530	0	1.44	10.69	164.38	114.12
1,770	688	0.4	1.44	1.92	234.1	320.37
1,770	688	0.4	1.36	1.41	222.81	348.51
1,770	688	0.4	1.28	0.95	199.9	370.52

*Field A, Beggs and Brill correlation

taken as a decisive criteria such that the correlation is considered applicable at the point if its error is less than the 10% accuracy limit. Otherwise, the correlation is considered not applicable.

Fig. 4 illustrates the applicability of the studied correlations on the gridded superficial velocity map of Field A. The symbol x at any grid indicates that the studied correlation absolute error at this grid is higher than the 10% limit, so that it is considered not applicable.

The other symbols indicate that the error of the corresponding correlation is less than the 10% limit and, therefore, applicable.

It is evident from these figures that no correlation can be applied on all the grids. For example, in the low gas velocity, high liquid velocity area of the map, the Hagedorn and Brown correlation can be applied while Beggs and Brill correlation is not applicable.

On the other hand, the opposite is true in the medium gas velocity, high liquid velocity part of the map. The points on the map are no longer overlapping and zonation of the application range of each correlation can be made objectively on the gridded map.

Expert data base

To minimize calculation errors of multiphase flow for any field, one needs to determine the best correlation at each point on the superficial velocity map.

The best correlation is the one which has the minimum absolute error at this point, with this error being less than the previously mentioned accuracy limit of 10% of the maximum measured gradient of the field.

Fig. 5A shows the best correlation at each grid for the superficial velocity map of Field A. In other words this is an expert data base for the best multiphase correlations for that field.

Fig. 5

EXPERT DATA BASE

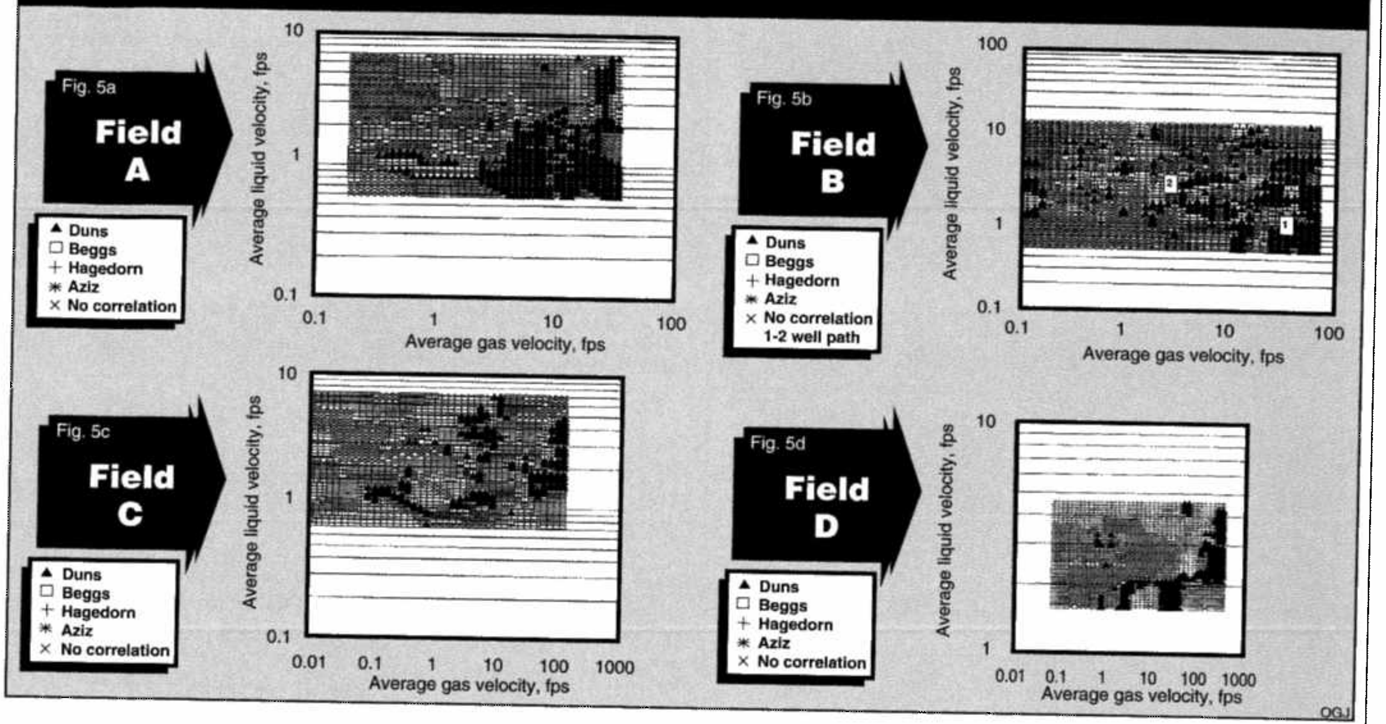
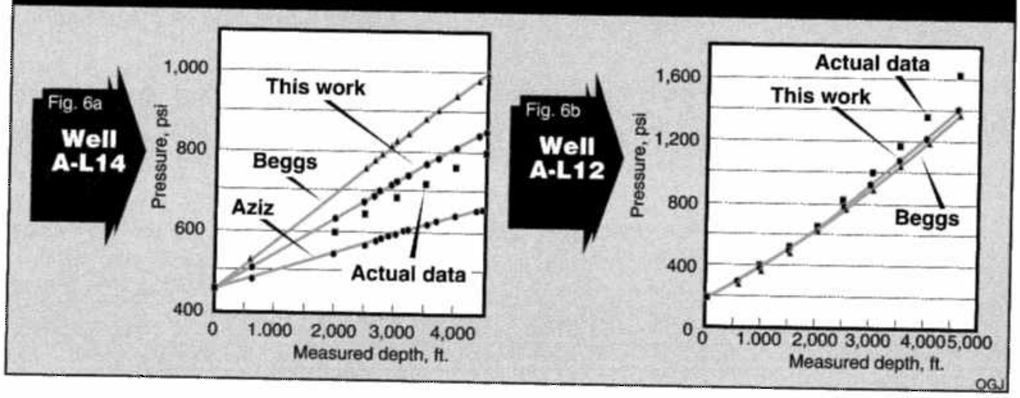


Fig. 6

DATA MATCH



The symbol x at any grid on the map means that all the correlations at this grid have errors larger than the 10% accuracy limit, so that no correlation is applicable with good accuracy at this grid. The other symbols indicate the best correlation of least error at this grid, with this error being less than the 10% limit.

This expert data base improves pressure-loss calculations for the field. Path 1-2 on Fig. 5B gives the well path starting from the well head at Point 1 to the bottom of the well at Point 2. The accuracy of calculations improves by using the best correlation at each point along the well path on the map. Consequently, multiple selective correlations should be used along the calculations path of the same well.

This technique of switching between the different correlations is a novel approach towards the development of a more accurate technique for pressure-drop calculations in multiphase flow.

Fig. 5 visualizes the expert data bases of Fields A, B, C, and D. It should be noticed that Fields C and D are producing with high water cut. The following observations concerning the applicability of correlations can be drawn from these figures as follows:

- Duns and Ros correlation is the best correlation for the mist flow regime (high gas velocity), however high water cut reduces its accuracy dramatically. This agrees with Duns and Ros' statement of unsuitability of this correlation when emulsions occur.[2] Both the Hagedorn and Brown, and Beggs and Brill correlations can give good results in cases of high water cut.
- No correlation can be satisfactorily applied in the transition region between bubble and slug regimes.

Master code

A master code incorporates the four multiphase-flow correlations. This master code is based on the expert data base of the specific group of data. It is based on the selective use of multiple correlations in the same well such that the calculations use the best correlation at each point in the well.

A sample of wells was taken to evaluate the new multiple-correlation approach. This sample included 20 wells from the four fields. Five wells were taken from each field representing the wells of minimum and maximum liquid rate and gas/liquid ratio in addition to an average well in the field. The absolute error at each interval in the well is defined as:

$$\text{Absolute error }\% = (\text{abs }(dp_{\text{calculated}} - dp_{\text{measured}}) \times 100)/dp_{\text{measured}}$$

The average absolute error of the well equals the sum of the absolute error of each interval divided by number of intervals in the well.

Table 3 shows the results