CHAPTER V

PROGRAMME VERIFICATION AND DISCUSSION

The programme developed by using C++ language is employed to solve the sizing problems of cryogenic and gas piping systems. The performance test of this programme is shown and discussed in this chapter. Three methods for testing the reliability of the programme are discussed below.

1. Comparison of the cryogenic and gas properties estimated by the developed programme to those of a commercial software named GASPAK
2. Comparison of pipe sizing calculated by the developed programme to reference data from existing installed pipe works, reference documents and an existing simulator such as PDROP version 2.04
3. Distribute this programme to implicated users to get feedback on its performance and to discuss about improvements of the programme and recommendations

5.1 Specific cases for verification of the developed programme

Several study cases are tested. They are deliberately simplified. The following worked examples are to be used for verification.

Case 1 (QCE 343-987)

Let's considers a situation in which two pieces of equipment use the liquid nitrogen supply. The so-called tunnel is operated virtually continuously while the so-called blender, is operated batchwise. It is possible, however, for the blender to operate on its own.

The required flow rates in the tunnel and blender are 0.55 kg/s and 0.25 kg/s respectively. Inlet pressure is 1.515 atm (absolute). The piping isometric sketch in this case is shown in figure 5.1.

Test condition: The pressure drop of system for polyurethane insulation is determined under each of the following conditions,

1.1 Maximum flow rate is supplied to tunnel and blender

1.2 Tunnel is operated only

1.3 Blender is operated only

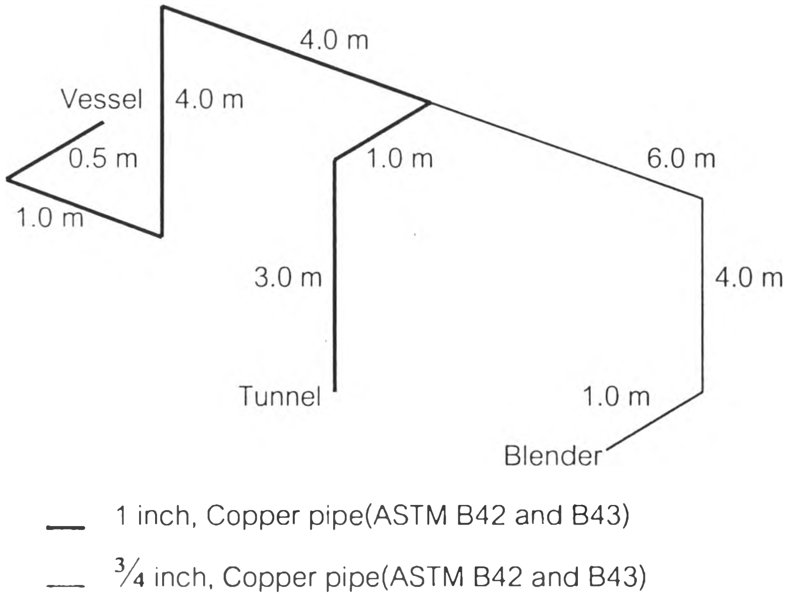


Figure 5.1 Piping isometric sketch of Case 1

Case 2 (QCE343-987)

Case 2 is to envisage a more refined process in which the liquid nitrogen usage is difficult to determine accurately. The process consisting of a 100-liter container that should be full of liquid nitrogen at the start of the process is operated repeatedly as a cycle. Vacuum insulation is used in this case with a gas lock in the pipe work. The mixed vacuum and polyurethane insulation is also tested in this situation.

The average flow rate of liquid nitrogen in the process is 80 Sm^3/hr. Figure 5.2 illustrates piping isometric sketch of this case. There is a globe valve at the exit of the vessel and a gate valve at process connection.

Test condition: The pressure drop of system under each of the following conditions is determined using the developed programme and referable software.

2.1 Vacuum insulation

2.2 Polyurethane insulation

2.3 Vacuum insulation and polyurethane insulation

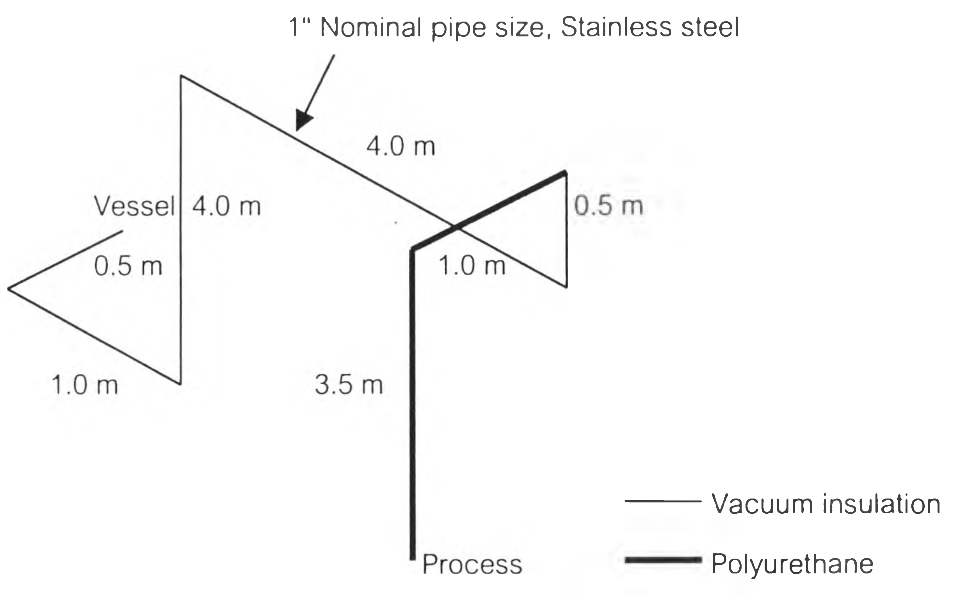


Figure 5.2 Piping isometric sketch of Case 2

Case 3 (QCE343-987)

This operating condition is similar to case 2 with neglecting the gas lock. The vacuum insulation is tested in the piping isometric sketch as shown in figure 5.3.

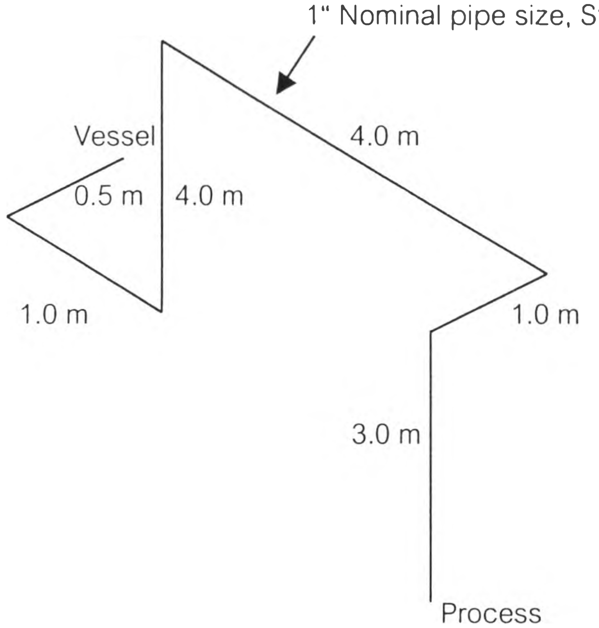


Figure 5.3 Piping isometric sketch of Case 3

Case 4 (Oxygen TPV system)

The abbreviation, TPV, refers to the equipment used to maintain the supply to a large gas user should the normal supply, usually from air separation plant and the gas compression system, fail for any reason. It can also be used to supplement the normal production in order to meet a high demand for short period. The main components of the TPV are a tank that stores the required liquid, a pump and a vaporizer.

The design flow rate of this case is 10000 Nm^3/hr at discharge pressure of 35 bar (gauge). The centrifugal pump is operated at suction pressure of 3 bar (gauge). The piping isometric sketches of both of suction and discharge are shown in figure 5.4 and 5.5, respectively.

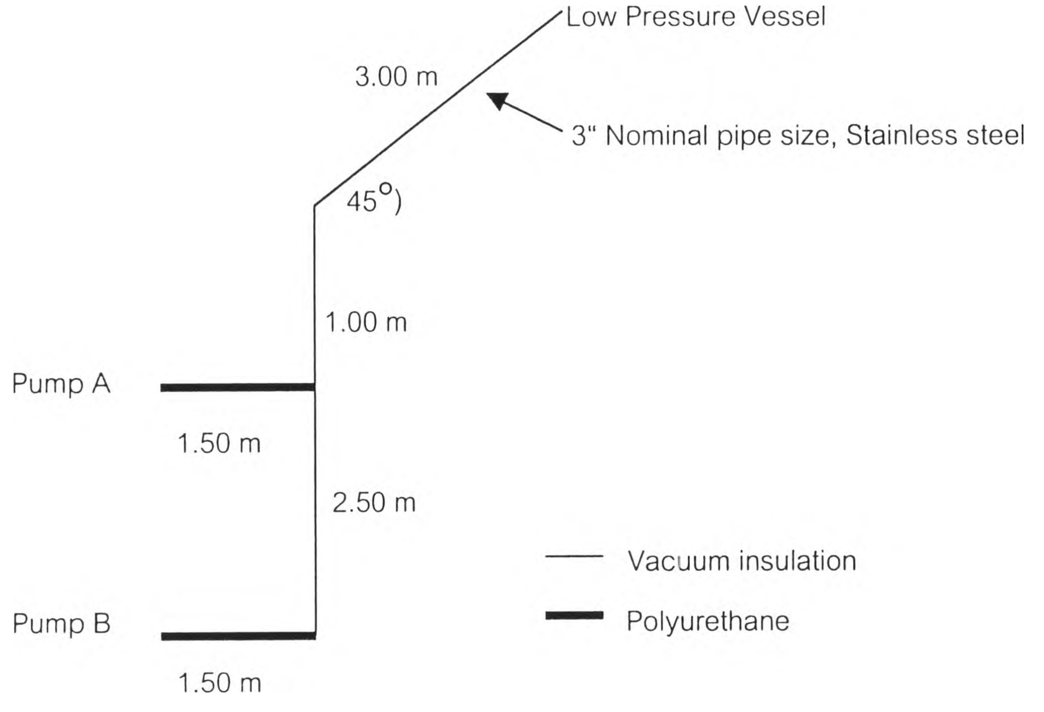


Figure 5.4 Piping isometric sketch of suction pipeline of Case 4

There is a ball valve at each pump suction and a globe valve at the exit of the vessel. This pipeline is installed in horizontal direction.

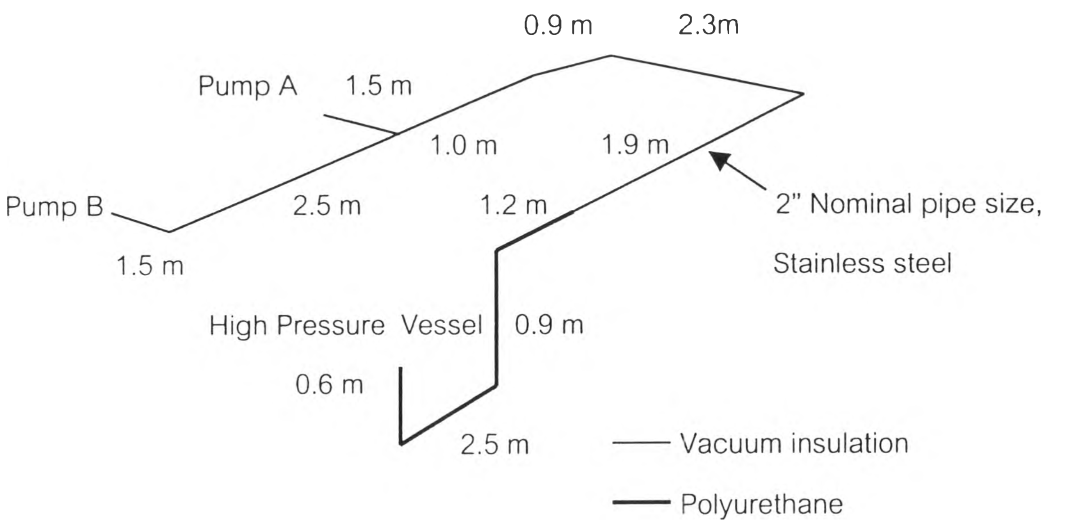


Figure 5.5 Piping isometric sketch of discharge pipeline of Case 4

Case 5 (Air separation plant)

There are the vacuum insulated pipelines installed for transfer liquid oxygen, nitrogen and argon from an air separation column to a storage tank. The simulation of this test is variation of the standard-volume flow rate of selected cryogens to find the pressure drop for 1-inch pipe installed in horizontal direction. The simulation result is compared with those of the existing software (PDROP2-4).

The simulated flow rates are 100, 200, 500, 1000 and 2000 Sm^3/hr respectively. The lengths of the pipeline are 80 metres for oxygen and 70 metres for nitrogen and argon.

5.2 Comparison of cryogenic and gas properties

The thermodynamic and transport properties models discussed in chapter III have been taken into account for testing the performance of developed programme. The prediction of those properties in the developed programme is interpolation of monographs that are provided in gas encyclopedia database. The comparison of the test results is shown in table 5.1.

By considering table 5.1, both over and under estimation in each property can be observed. The viscosity and density have shown some difference in every test because some interpolation occurs at passage from the liquid state to gaseous state. This is the limitation of interpolation technique, which is the simple category to predict those properties by the user who should not have knowledge of thermophysical concepts.

Experimental data on the density of either the saturated gas or liquid phase were taken at single phase conditions very close to the saturation boundary. Then they were used for extrapolating to the actual two-phase conditions. Therefore, more uncertainty

Table 5.1 The Comparison of Calculated Properties to GASPAK

	GASPAK	CryoSim	%DIFF	GASPAK	CryoSim	%DIFF	GASPAK	CryoSim	%DIFF
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	4.01325	4.01325		4.01325	4.01325		4.01325	4.01325	
Temperature(K)	308.15	308.15		308.15	308.15		308.15	308.15	
Density(kg/m^3)	5.02278	5.039625	-0.335372	4.39011	4.404623	-0.330584	6.2704	6.277658	-0.11575
Viscosity(cP)	0.0211033	0.021201	-0.4629608	0.0183734	0.018225	0.807689	0.023475	0.023275	0.85197
Compressibility factor	0.997948	0.997879	0.0069142	0.999531	0.999504	0.002701	0.997923	0.997779	0.01443
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	6.01325	6.01325		6.01325	6.01325		6.01325	6.01325	
Temperature(K)	308.15	308.15		308.15	308.15		308.15	308.15	
Density(kg/m^3)	7.53352	7.556679	-0.3074127	6.57927	6.601294	-0.334748	9.40487	9.416369	-0.122266
Viscosity(cP)	0.0211252	0.021235	-0.5197584	0.0184043	0.018258	0.794923	0.0235101	0.023318	0.817096
Compressibility factor	0.996935	0.996995	-0.0060184	0.999327	0.99929	0.003702	0.996902	0.996722	0.018056
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	11.01325	11.01325		11.01325	11.01325		11.01325	11.01325	
Temperature(K)	308.15	308.15		308.15	308.15		308.15	308.15	
Density(kg/m^3)	13.8324	13.888584	-0.4061768	12.0551	12.096869	-0.346484	17.2685	17.295399	-0.155769
Viscosity(cP)	0.0211856	0.021323	-0.6485537	0.0184832	0.018341	0.769347	0.0236021	0.023425	0.750357
Compressibility factor	0.99443	0.994361	0.0069386	0.998899	0.998832	0.006707	0.994392	0.994322	0.007039

Table 5.1 The Comparison of Calculated Properties to GASPAK (Continued)

	GASPAK	CryoSim	%DIFF	GASPAK	CryoSim	%DIFF	GASPAK	CryoSim	%DIFF
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	21.01325	21.01325		16.01325	16.01325		151.01325	151.01325	
Temperature(K)	288.15	288.15		308.15	308.15		308.15	308.15	
Density(kg/m^3)	28.4961	28.71938	-0.7835458	17.5335	17.596282	-0.358069	245.739	245.07679	0.269478
Viscosity(cP)	0.0202523	0.020418	-0.8181787	0.0185654	0.018428	0.740086	0.0281946	0.028462	-0.948409
Compressibility factor	0.984933	0.98492	0.0013199	0.998589	0.998491	0.009814	0.95816	0.962015	-0.402334
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	41.01325	41.01325		151.01325	151.01325		151.01325	151.01325	
Temperature(K)	313.15	313.15		323.15	323.15		323.15	323.15	
Density(kg/m^3)	51.3121	51.672656	-0.7026725	151.345	150.945393	0.264037	230.847	230.09622	0.325229
Viscosity(cP)	0.0219399	0.022051	-0.5063833	0.0221944	0.022031	0.736222	0.0287465	0.028918	-0.596594
Compressibility factor	0.982359	0.981438	0.0937539	1.04035	1.042196	-0.17744	0.972623	0.975782	-0.324792
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	151.01325	151.01325		1.01325	1.01325		1.01325	1.01325	
Temperature(K)	308.15	308.15		273.15	273.15		273.15	273.15	
Density(kg/m^3)	197.49	196.814714	0.3419343	1.25042	1.24118	0.738952	1.78395	1.784552	-0.033745
Viscosity(cP)	0.0250425	0.025384	-1.3636817	0.0166902	0.016588	0.612335	0.0211436	0.021029	0.542008
Compressibility factor	0.955048	0.963199	-0.853465	0.999534	0.999535	-0.0001	0.999057	0.99905	0.000701

Table 5.1 The Comparison of Calculated Properties to GASPAK (Continued)

	GASPAK	CryoSim	%DIFF	GASPAK	CryoSim	%DIFF	GASPAK	CryoSim	%DIFF
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	3	3		3	3		3	3	
Temperature(K)	100	100		100	100		100	100	
Density(kg/m^3)	1090.87	1090.9922	-0.0112021	10.7606	10.765	-0.04089	15.5168	15.5099	0.044468
Viscosity(cP)	0.154309	0.038764	74.878977	0.00690539	0.021196	-206.9486	0.00834451	0.045944	-450.5895
Compressibility factor	0.0105844	0.0106	-0.1473867	0.939339	0.93898	0.038218	0.928916	0.9294	-0.052104
Fluid	Oxygen(78)	Oxygen		Nitrogen(86)	Nitrogen		Argon(83)	Argon	
Pressure(bara)	7.5	7.5		7.5	7.5		7.5	7.5	
Temperature(K)	100	100		100	100		100	100	
Density(kg/m^3)	1092.15	1902.0347	-74.155079	30.5285	358.3734	-1073.898	1313.6	1312.8529	0.056878
Viscosity(cP)	0.155111	0.108794	29.860551	0.00718976	0.053406	-642.8064	0.1844	0.130644	29.15184
Compressibility factor	0.02643	0.02645	-0.0756716	0.82774	0.441325	46.68314	0.0274318	0.02745	-0.066346

was obtained. There is no the thermodynamic equation of state, EOS, accurately predicting liquid-vapor properties at its saturation boundary because of the rapid changes of phase. In addition, a lacking of experimental data for saturated vapor properties also makes its more difficult. The result of these combined factors is less accuracy in the calculated thermophysical properties at the saturated liquid-vapor condition.

However, there is no reasonable way to estimate errors in the critical region. The errors are comparatively large, and calculations in this region should be avoided if possible. For instance, viscosity at pressure of 150 bar (gauge) and temperature of 308.15 K is about 1.4% under estimated if compared with the reference data.

5.3 Comparison of pipe sizing by the developed programme to reference data sources

The references employed in this work are the results of calculation from PDROP2-4 and QCE343-987. The dryness fraction and pressure drop profiles calculated by the developed programme have been compared to those of the references. The test results are based on the different type of insulation, pipe size and pipeline configuration.

It is convenient to show the difference of the calculation results by using graphs. The results of dryness fraction at the outlet of each pipe length from the developed programme are close to results of QCE343-987. Effect of different heat inleak from ambient air through the insulation in same basis as equation (3-29) was considered. The heat inleak for various insulations are given in appendix I.5 of QCE343-987 by assuming the inner pipe is contained with an outer 150 mm outside diameter of PVC pipe.

Considering case1.1a, the heat inleak for polyurethane insulation is 0.0258 kJ/s/m for liquid nitrogen but the result of developed programme is 0.0111346 kJ/s/m in the same configuration of 1 inch inner pipe and 150 mm outer pipe. The mean thermal conductivity of the insulation used in this calculation is the same value as that of the reference. Therefore, the important parameters are outside diameter of outer pipe and the mean convective heat transfer coefficient.

The mean convective heat transfer coefficient calculated from equation (3-24) or (3-25) has an accuracy about ±25%. It is used in the developed programme to calculate heat inleak by using the thermophysical properties of fluid at saturated pressure of inlet pressure. The saturated condition used in QCE is the saturated pressure and temperature at boiling point of nitrogen. Therefore, the gas quality calculated from a basis of fixed heat inleak and latent heat of vaporization at that saturated condition is different from the calculated result of developed programme (figure 5.6). These differences become smaller if using fluid properties at the same condition.

Figure 5.7 a) and b) display the results of gas quality at the exit of each pipe section. For the pipe section no. 4, 5 and 6 of case 1.1a, dryness fraction calculated from the developed programme is higher because QCE use a fixed heat inleak to calculate gas quality even though pipe size is changed.

In the developed programme, the pipe size and flow rate changing are considered for prediction of the gas quality. The value of heat inleak should become smaller as pipe size is decreased as shown in figure 5.8. The maximum error of heat inleak is 62.4% for polyurethane insulation in case 1.1 and 1.3.

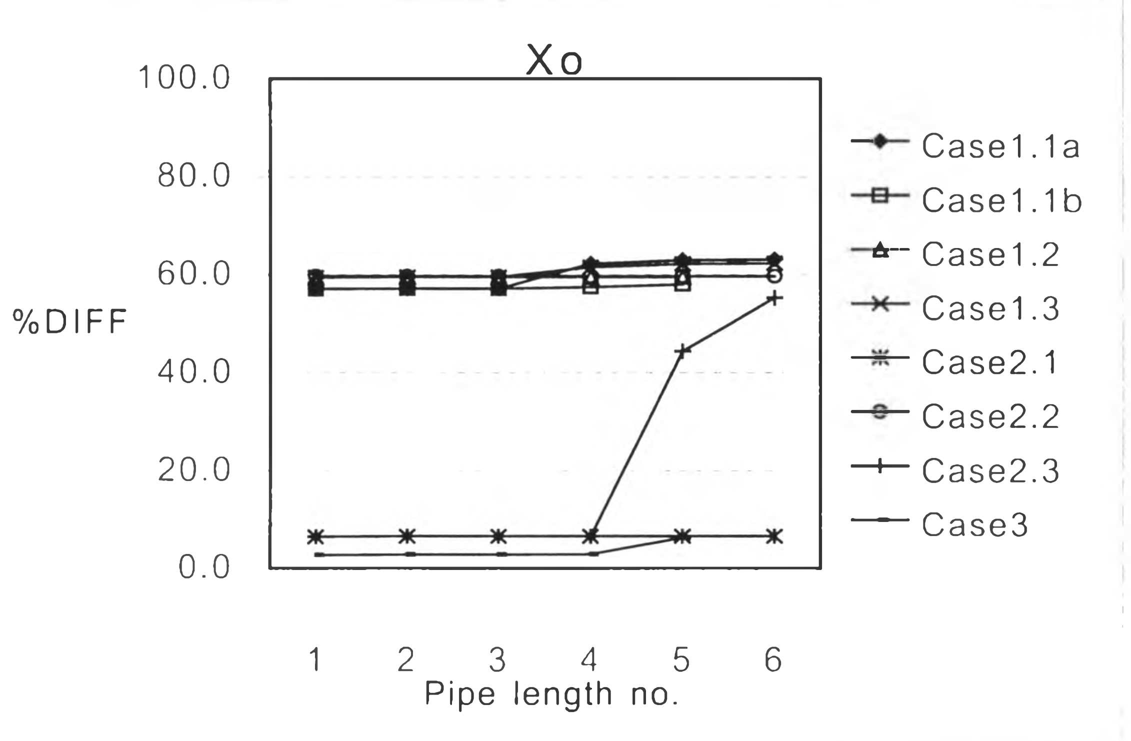
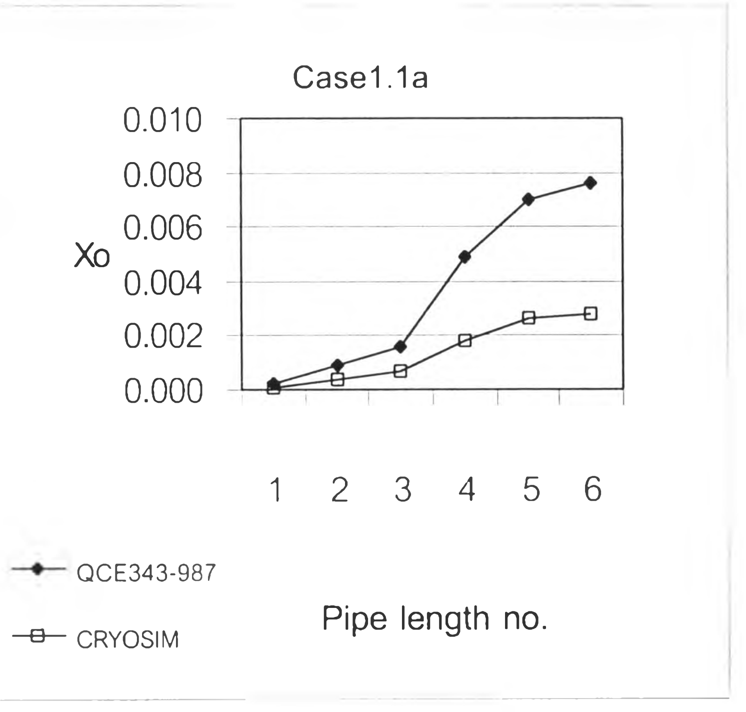
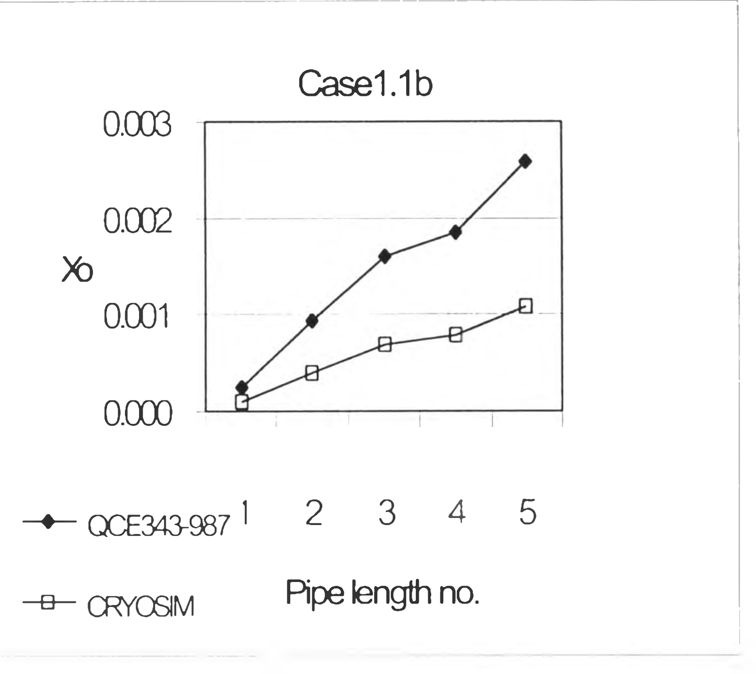


Figure 5.6 Summary of the relative error for outlet dryness fraction

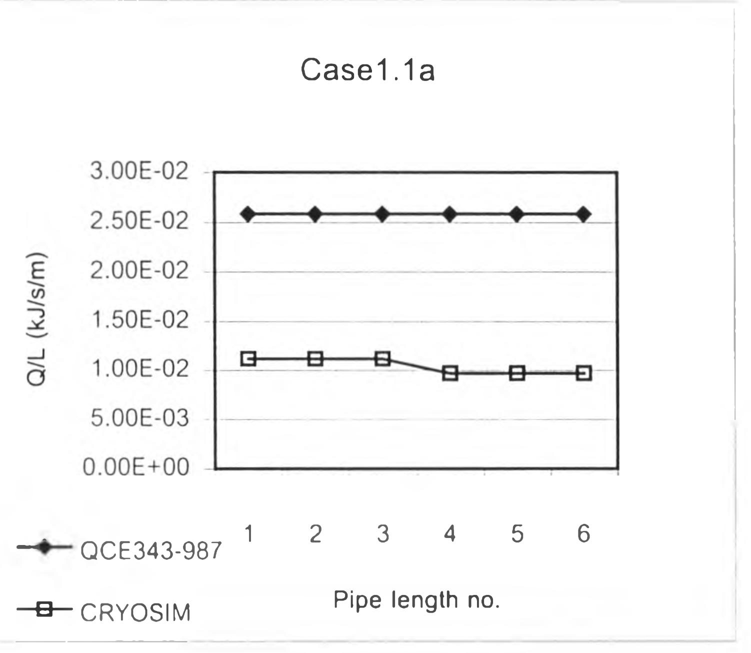


a) Maximum flow rate is supplied to blender

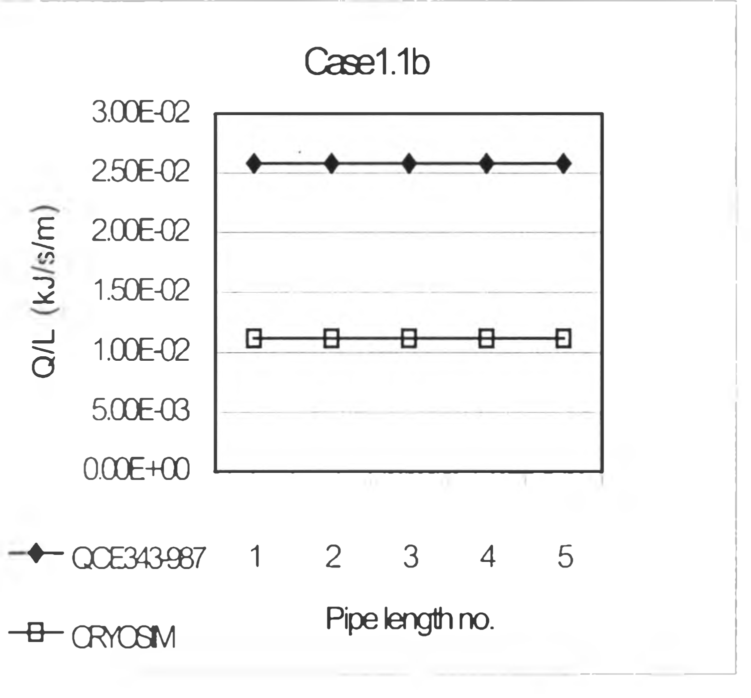


b) Maximum flow rate is supplied to tunnel

Figure 5.7 The results of outlet dryness fraction for case 1.1.

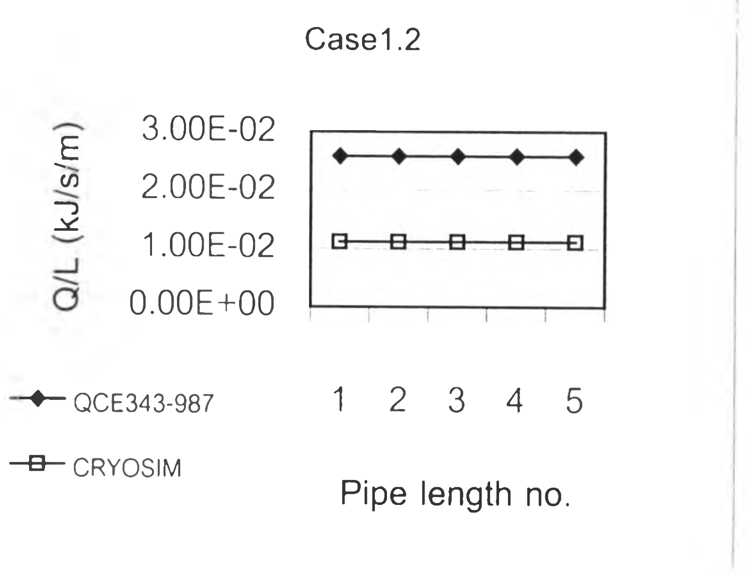


a) Maximum flow rate is supplied to blender

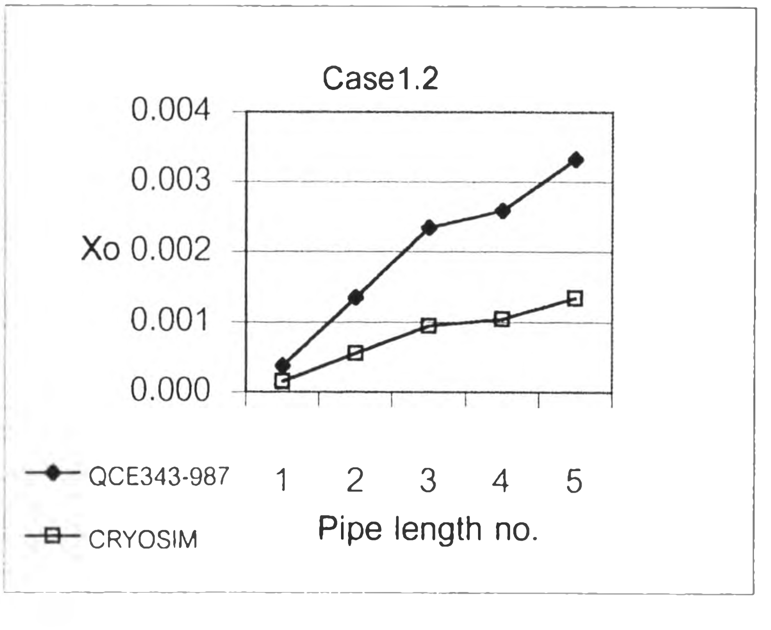


b) Maximum flow rate is supplied to tunnel

Figure 5.8 The result of heat inleak for case 1.1

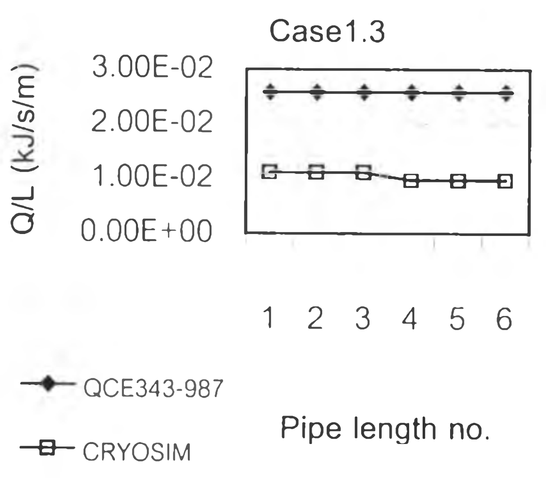


a) Heat inleak

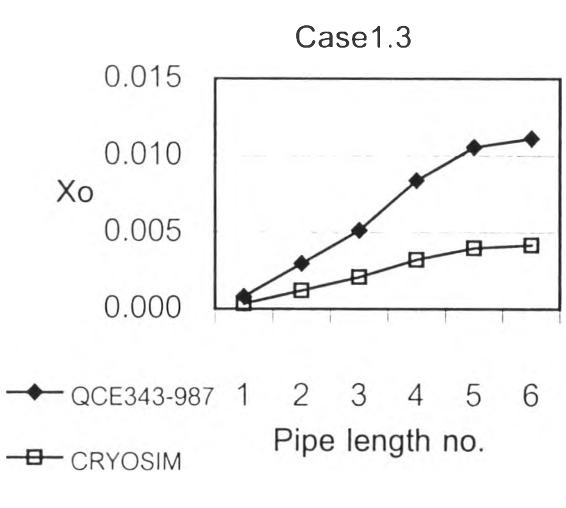


b) Outlet dryness fraction

Figure 5.9 The results of outlet dryness fraction and heat inleak for case 1.2

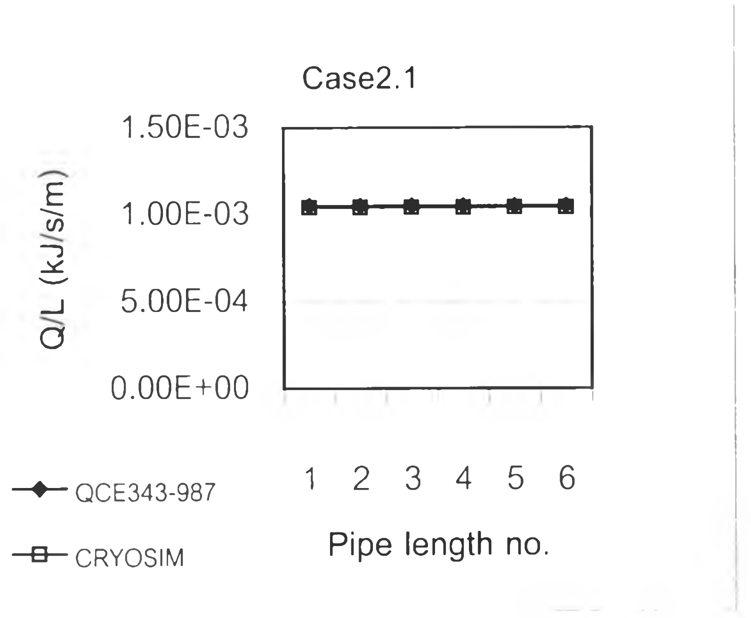


a) Heat inleak

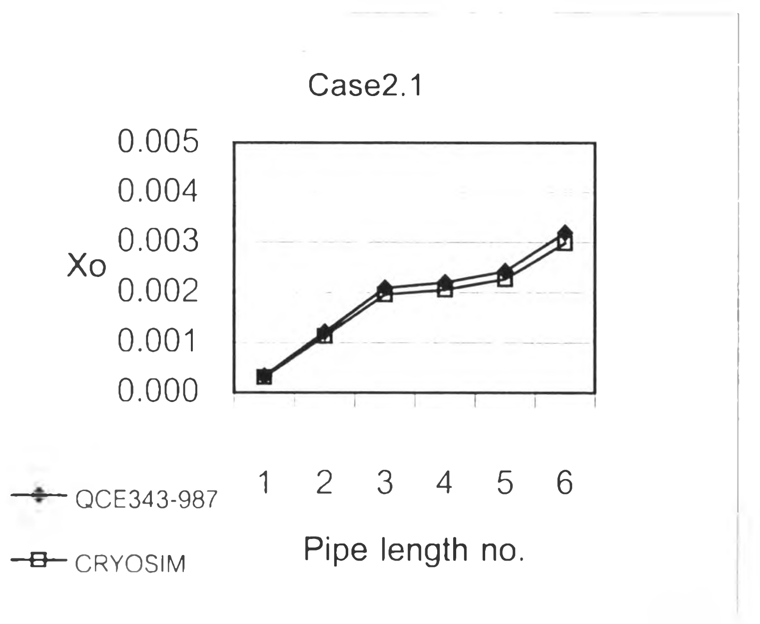


b) Outlet dryness fraction

Figure 5.10 The results of outlet dryness fraction and heat inleak for case 1.3.

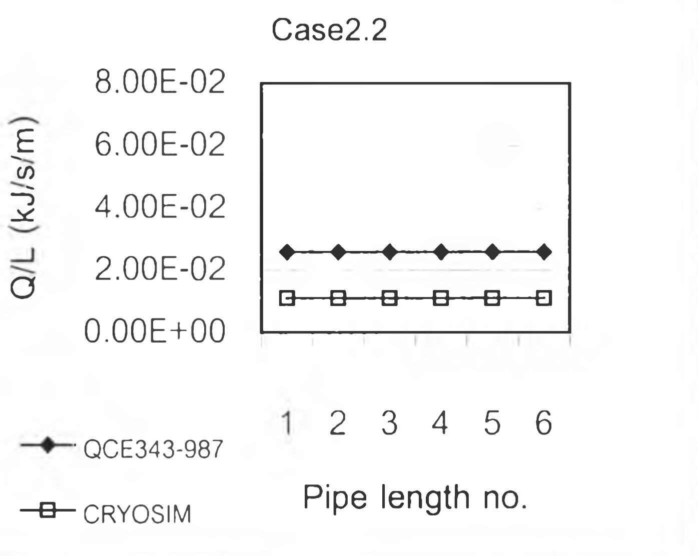


a) Heat inleak

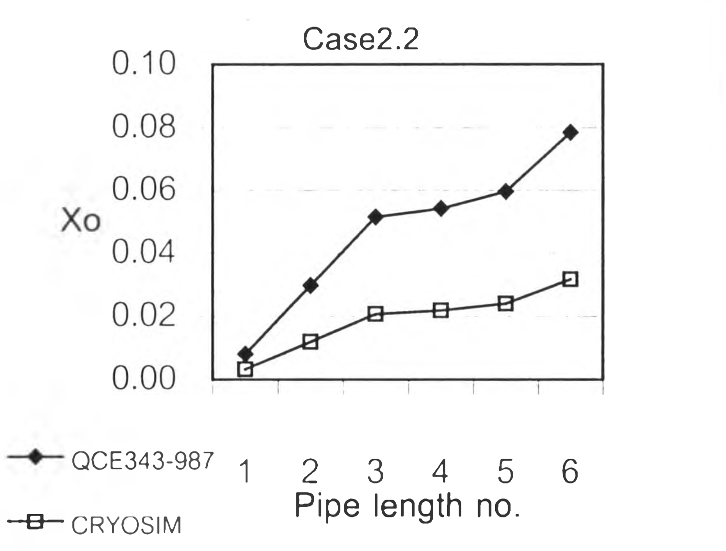


b) Outlet dryness fraction

Figure 5.11 The results of outlet dryness fraction and heat inleak for case 2.1.

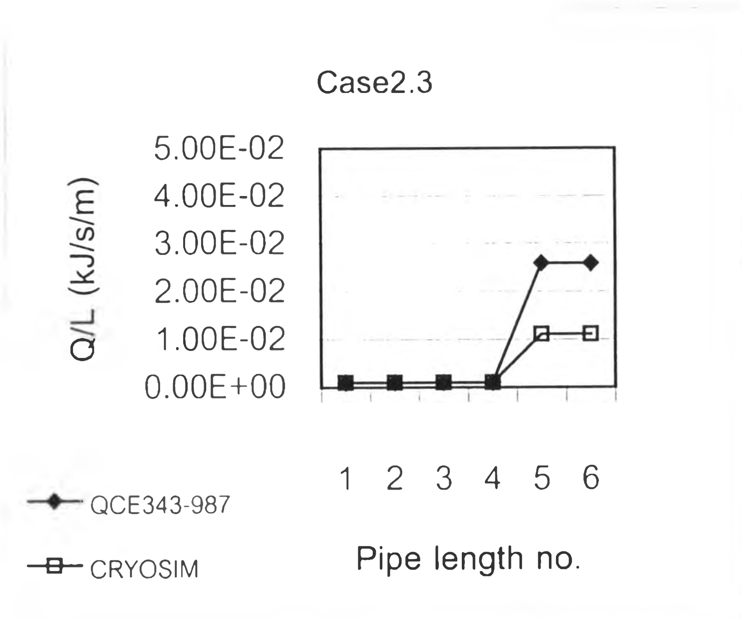


a) Heat inleak

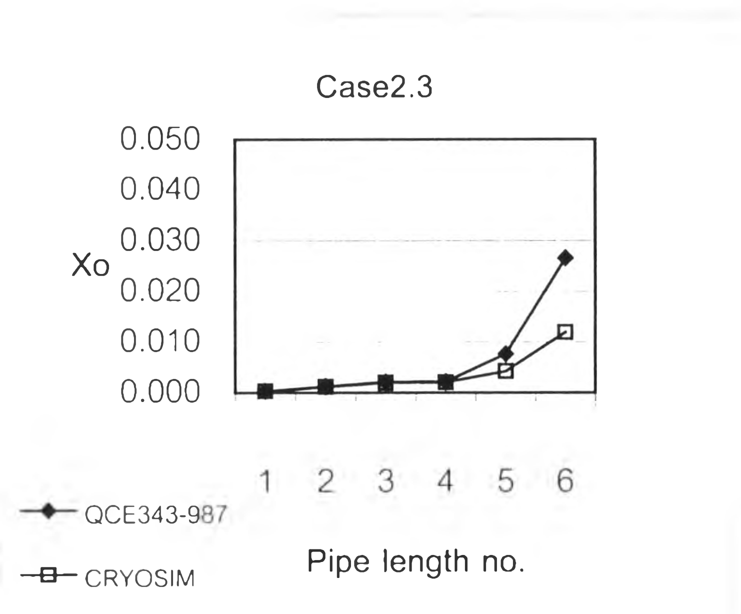


b) Outlet dryness fraction

Figure 5.12 The results of outlet dryness fraction and heat inleak for case 2.2.

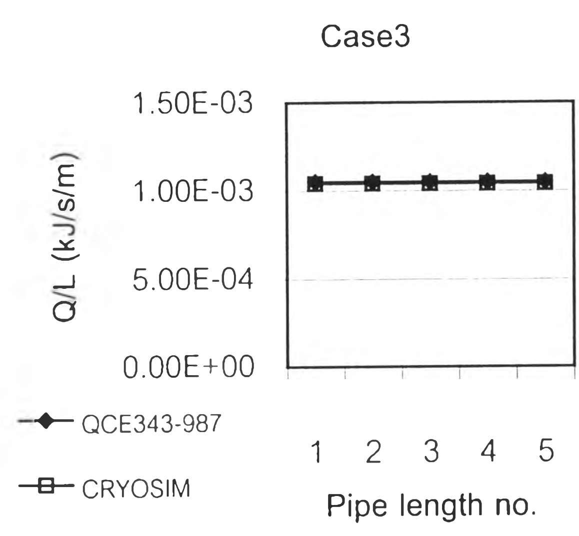


a) Heat inleak

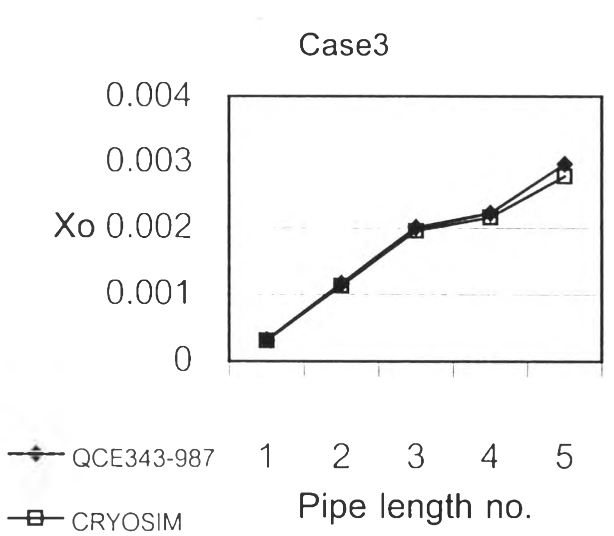


b) Outlet dryness fraction

Figure 5.13 The results of outlet dryness fraction and heat inleak for case 2.3.



a) Heat inleak



b) Outlet dryness fraction

Figure 5.14 The results of outlet dryness fraction and heat inleak for case 3.

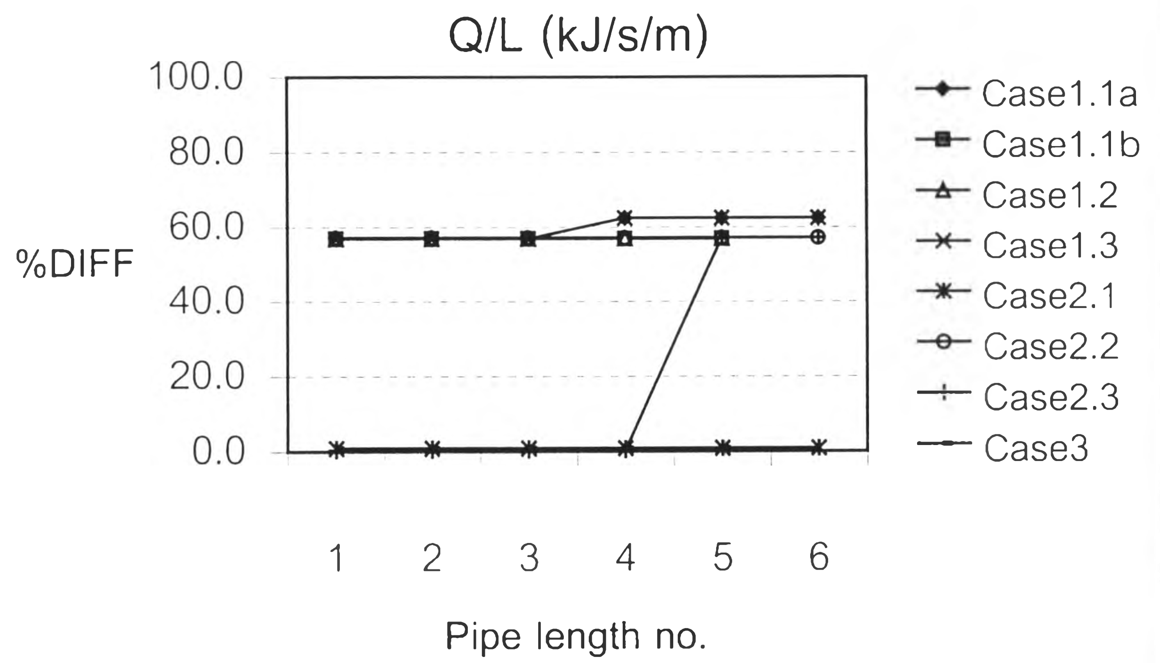


Figure 5.15 Summary of relative error for heat inleak

Figure 5.9 and 5.10 display the calculation results of case 1.2 and 1.3, respectively. As can be seen, it is almost the same as that of case 1 although the flow rate is changed. The gas quality is increased with a decrease in flow rate of fluid. The results from case 2 and 3 are used to proof the effect of fluid properties and insulation type for prediction of gas quality as displayed in figure 5.11 to 5.14. For case 2.1and 3, the maximum errors of heat inleak and gas quality are 0.89% and 6.55% respectively. The error of estimated heat inleak by using equation (3-27) is very low. Moreover, the gas quality varies in small range with the different of input fluid properties. Considering case 2.2 and 2.3, the heat inleak estimated by developed programme to polyurethane insulation is about 10.55 times higher than that corresponding to vacuum insulated pipe. The relative error distribution of heat inleak for all cases shown in figure 5.15 has similar pattern as compared with that of exit gas quality.

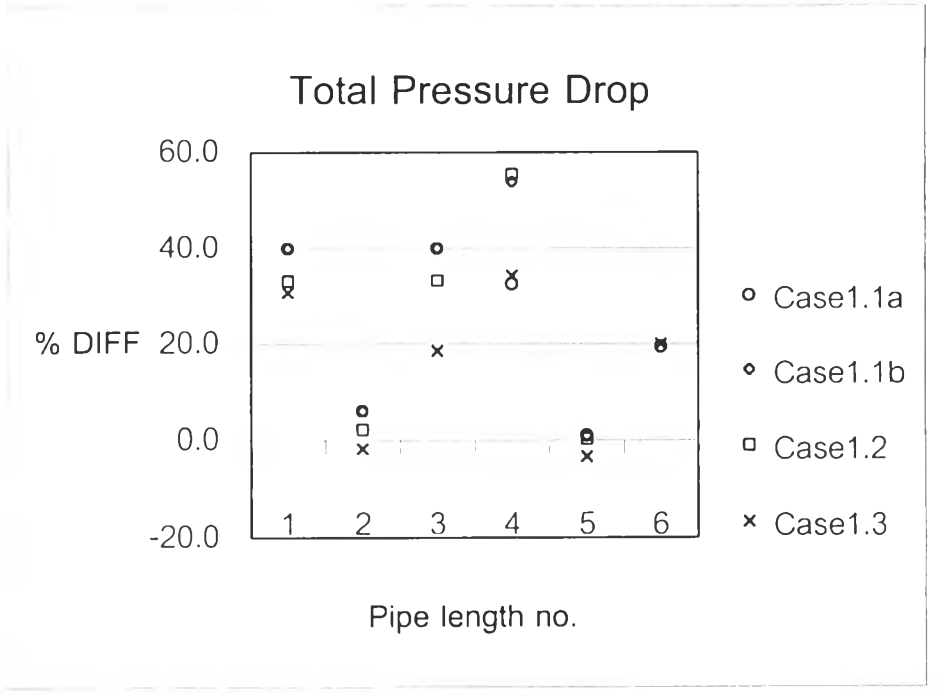


Figure 5.16 Summary of relative error for total pressure drop of case 1

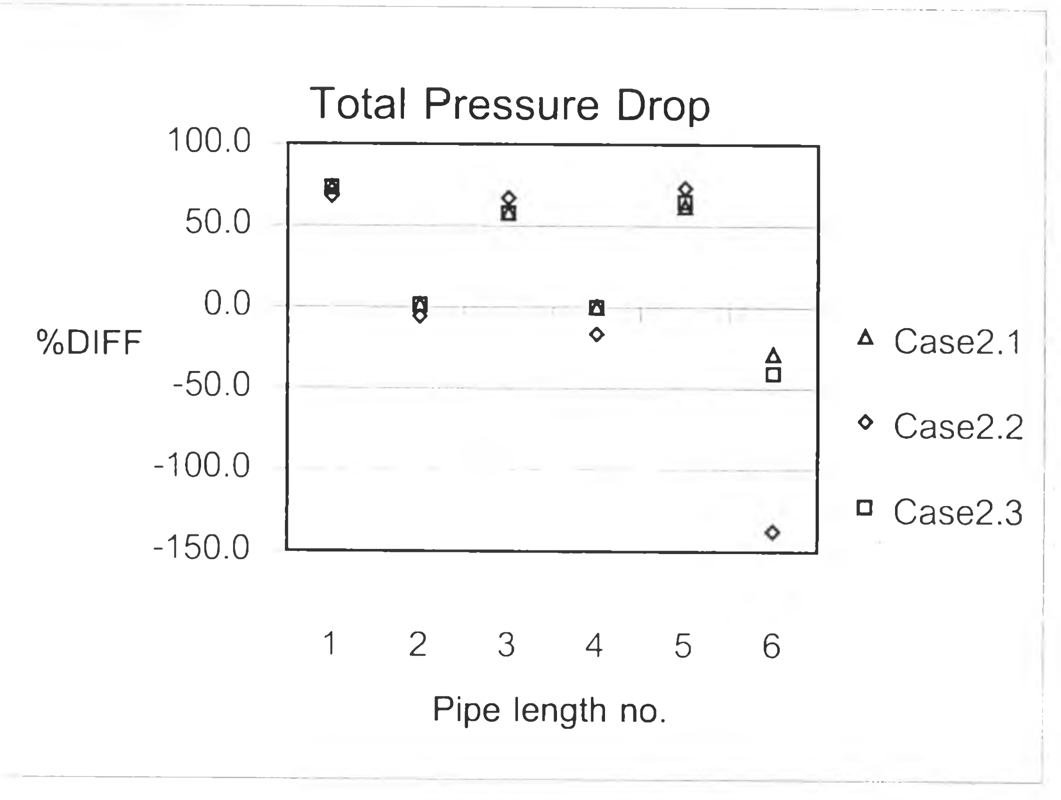


Figure 5.17 Summary of relative error for total pressure drop of case 2

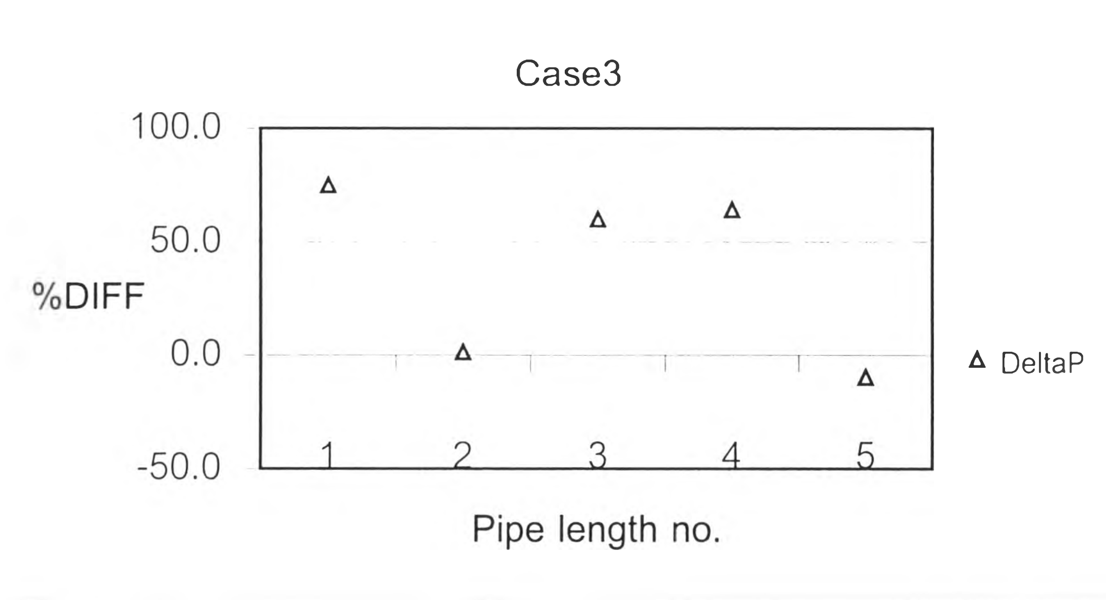


Figure 5.18 Summary of relative error for total pressure drop of case 3

The results of total pressure drop in each pipe section of case 1, 2 and 3, which are calculated by developed programme and reference source are shown in figure 5.16, 5.17 and 5.18, respectively. Results of pressure drop in vertical upflow are over estimated in small range. When lines have both horizontal and vertical legs of the same line size, slugging will occur preferentially in the vertical leg. The prediction of friction pressure loss is high for slug flow. For the vertical downflow of case 2.2, the pressure drop is much under estimated because gas locking takes place in the pipe work. The gas locking can be identified by the highest gas quality in each pipe length. Therefore, flooding liquid increases pressure drop, reduces the available static head, and can drastically reduce the capacity of pipe. In most installations, the pressure required to raise the liquid or pressure gain from falling liquid would be more significant than the pressure loss in overcoming friction.

The flow mechanism in all cases is turbulent-viscous flow, which is associated with small dryness fractions. All calculations are based on turbulent-turbulent condition with different friction factor. The Fanning friction factor in QCE is calculated with the with different friction factor. The Fanning friction factor in QCE is calculated with the explicit Chen equation but the developed programme makes use of Churchill's equation, which covers the complete range of Reynolds number. The error in using Churchill's equation is less than ±1% according to the work of Swamee and Jain. The two-phase multiplier is a function of dryness fraction and stream pressure for both calculations.

Considering case 4, the calculated results from the developed programme and reference software are shown in table 5.2. Difference of this case can be also described by the previous reasons.

Table 5.2 Comparison of total pressure drop of pipe work in case 4

Total pressure drop(mbar)	PDROP2-4	CRYOSIM	%DIFF
Suction	16	10.4547	34.65
Discharge	1309.4	686.946	47.54

The test conditions in case 5 are turbulent-turbulent flow condition. Therefore, the two-phase multiplier correlation of both programs can be employed to predict friction pressure drop of pipeline by changing the flow rate, upstream pressure and type of cryogen. The calculation results are shown in table A-6 of appendix A.

The maximum error of pressure drop is 56.25% under estimated at lowest flow rate and is 20.50% over estimated at highest flow rate. The gas quality at highest flow rate is lower than 0.001. It effects calculation of the reference programme by changing the calculation mode to single phase flow. The dryness fraction becomes closed to 0.001 by increasing the flow rate and reducing upstream pressure. The difference between results of the developed programme and those of the reference programmes increased with flow rate as shown in table A-6.

5.4 User recommendations

This programme is developed for propose of sizing pipeline and estimating the pressure drop for both single and two-phase flows of cryogenic fluids. The demo version of developed programme is distributed to project engineers, process engineers, and engineering manager of Thai Industrial Gases PLC. and BOC Group. They have recommendations for the improvement of programme as below.

They do not understand some calculations in main programme and some tools in the database because the demo version does not have the help file to assist them to learn how to use the developed programme in the right way.

Some of them test this programme with the existing simulator such as PDROP2-4 and FLOWMATE, which are developed in BOC Group, the results of comparison are different in term of value for the pressure loss but have the same trend. Pipe size obtained from the prediction of this programme agrees with the commercial pipe size. However, this programme can not provide pipe schedule information that is compatible with stream pressure.

For the user interface, users commented that it is better than existing programme running on DOS. The databases of fluid properties are easy to keep and be modified. They suggested improving the programme to provide other functions, such as displaying graph, picture or providing multimedia services.

For the main programme, it should have some guiding messages that can help the user to identify the limitation or boundary of inputs. The graphic mode used to sketch the configuration of piping system should be modified as be worked in three dimensions. The calculation report should be identified some parameters for the user who does not get used to two-phase flow calculation.