CHEMICAL PROCESS DESIGN ON A PROGRAMMABLE CALCULATOR

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PREFACE

Rapid advances in semiconductor technology in recent years have brought the small calculator, with significant computational power and at reasonable cost, within reach of every technician or engineer in almost every level of industry. The introduction of the programmable calculator marks a significant advance in this technology and opens a new realm of possibilities to the engineer, student, consultant and teacher—to name just a few. Now the engineer can quickly solve, on a pocket-size calculator, complex and iterative-type problems that were once reserved for very large and complex computers.

This book is intended primarily for, but not limited to, the practicing process engineer who must design and optimize process equipment on a regular basis. A variety of programs are offered that will allow the engineer to look at "what-ifs" in design or sizing alternatives while reducing computational errors. The speed and versatility of the programmable calculator not only provides the user additional time to explore alternative solutions to design problems, but also can play a key role in the stimulation of other ideas.

This book is unique in that sufficient information (equations, theory, background, flowcharts, and instructions) is presented to allow both the TI-59 user and users of other calculators with a different programming language to benefit. Even users of tabletop computers that require BASIC or FORTRAN can readily construct programs from the equations and flowchart logic presented. All programs contain examples that will help the user become thoroughly familiar with the operation of the program.

Most of the programs presented have a self-prompting feature which allows easy use of the programs, by either the novice or the experienced calculator user, with a minimum of instruction. In this mode of operation the calculator asks a series of questions which are answered by the user. When the last question is answered, the calculator will continue through the program to produce a solution to the problem. Although a printer is required to use the self-prompting feature, these programs have been structured to allow easy operation by users without printers. The solutions to all programs, including intermediate results, are stored in data registers for easy recall at the completion of each program. The printed results of each program are formatted so that the tape can be cut and pasted directly onto any associated calculation sheets for a permanent record.

Generally, all programs listed in this book were kept as straightforward and simple as possible. Absolute addressing and indirect addressing were minimized. However, for the most effective use of this material it is assumed that each user has a fairly good working knowledge of his or her calculator.

The book is divided into seven chapters, each of which covers at least one aspect of process design that must be addressed by almost every practicing process engineer at one time or another. All programs presented in this book are based on the experiences of many process engineers for the sizing and optimization of numerous types of process equipment and associated piping. Programs listed cover a wide range of process activities including pipe, pump, and compressor sizing; vessel, dryer, and tower sizing; multicomponent separation; heat transfer, and physical properties of fluids. Several handy utility routines are included that should make life easier for the user.

Programmed magnetic cards for any of the TI-59 programs listed in this book are available for $7.50 each. Send stamped, self-addressed envelope and blank cards to be programmed to:

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Very special thanks go to Mr. Joe Chao who has offered constructive criticism and many suggestions in the preparation of this book. Joe also wrote the programs for the double-pipe heat exchanger and the two-dimensional linear interpolation that appear in this book.

Special thanks are due my wife Beth for her long and grueling hours at the typewriter trying to decipher my scribblings and extended equations containing unfamiliar symbols in both English and Greek.

W. Wayne Blackwell

CONTENTS

1
FLUID FLOW

Typically, process piping costs 20 percent or more of the total plant investment, and energy usage (pressure drop) and continued maintenance add additional costs. It is evident from this that sound sizing practices can have a substantial impact on overall plant economics. Generally, it is the process engineer's responsibility to optimize pressure drop in piping and equipment with compressor or pump horsepower to determine the most economic conditions. This task requires many trial-and-error calculations for which the programmable calculator is well suited.

Several pipe-sizing programs covering a wide range of flow conditions are presented in this chapter. Correlations of both single- and two-phase flow are presented for general line sizing, and a special program for sizing steam condensate headers is included. Pressure drop in packed beds is covered by the familiar Ergun equation, and a comprehensive program is presented for those engineers who must size relief valves for either vapor or liquid service.

A special program for sizing control valves for vapor, liquid, and steam service is included in this chapter as well as a time-saving program for the conversion of pipe fittings to equivalent length of line.

For those users who require the results of these programs in metric units, a conversion table is given in the appendix.

The Calculation of Compressible Isothermal Flow in Pipelines

It is generally conceded that the flow of a compressible fluid through long pipelines approaches isothermal conditions, i.e., flow at constant temperature.

Usually the pressure drop in these pipelines is large relative to the inlet pressure, and because of the appreciable change in density and velocity the usual form of the Darcy pressure-drop equation is not considered applicable. However, an accurate determination of the flow characteristics that apply to this region can be made by applying the complete isothermal equation:

$$w^2 = \left\{\frac{144\, gA^2}{V_1[FFL/D + 2 \ln (P_1/P_2)]}\right\}\left\{\frac{P_1^2 - P_2^2}{P_1}\right\} \tag{1-1}$$

A complete derivation of this equation can be found in an article by Kern.[1]

A modification of Eq. (1-1) was programmed to solve for either gas flow or gas pressure at the end of the pipeline. Also programmed was the ideal-gas density equation for rapid calculation of densities when gas molecular weight and temperature are known. Ideal density can be corrected for high-pressure conditions with a compressibility factor. See Chap. 6 for additional information on the calculation of gas density.

The Equations The calculator was programmed to solve the following equations:

$$W = 1337.024 \left\{\left[\frac{\rho d^4}{FF12L/d + 2 \ln (P_1/P_2)}\right]\left[\frac{P_1^2 - P_2^2}{P_1}\right]\right\}^{0.5} \tag{1-2}$$

$$P_2 = \left\{P_1^2 - \left[FF12L/d + 2 \ln \frac{P_1}{P_2}\right]\left[\frac{W^2 P_1}{\rho d^4 (1337.024)^2}\right]\right\}^{0.5} \tag{1-3}$$

$$\mathrm{Re} = \frac{6.31W}{d\mu} \qquad (1\text{-}4)^{(2)}$$

$$FF = \frac{64}{\mathrm{Re}} \quad \text{for Re} \le 2000 \qquad (1\text{-}5)^{(2)}$$

$$FF = \left\{2 \log \left[\frac{3.24\varepsilon}{d} + \left(\frac{7}{\mathrm{Re}}\right)^{0.9}\right]\right\}^{-2} \quad \text{for Re} > 2000 \qquad (1\text{-}6)^{(3)}$$

$$\rho = \frac{(\mathrm{MW})(P)}{RT} \tag{1-7}$$

NOMENCLATURE

P_1 = initial gas pressure, psia
P_2 = terminal gas pressure, psia
d = pipe inside diameter, in
D = pipe inside diameter, ft
L = pipe length, ft

W = gas flow, lb/h
w = gas flow, lb/s
ρ = gas density, lb/ft^3
$\overline{V}_1$ = specific volume at initial conditions, ft^3/lb
μ = gas viscosity, cP
ε = pipe roughness, ft
MW = molecular weight of gas
P = gas pressure, psia
FF = friction factor
R = gas constant, 10.73
T = absolute temperature, °R
g = acceleration of gravity, 32.2 ft/s^2
A = cross-sectional area of pipe, ft^2

Using the Program

Complete operating instructions for this program are shown in Table 1-1. User-defined keys are given in Table 1-2, and data register contents are shown in Table 1-3. The program flowchart is shown in Fig. 1-1. Since the program requires 561 program steps and 40 data registers, the calculator must be partitioned to 639.39 before either stepping in the program or reading it in from prerecorded magnetic cards. The first time the program is stepped into the calculator, certain constants must also be entered into the data registers before the program is stored on magnetic cards. These constants are outlined in Table 1-3.

This program is self-prompting, and once the correct label is pressed the user need only answer the questions presented and continue the program by pressing R/S.

Label A will calculate the maximum gas flow rate for a given line size and pressure drop. Label B will calculate the terminal pressure in a given size pipeline with a known gas flow rate, and label C will calculate the ideal-gas density.

After all questions have been answered, the calculator proceeds to carry out the computations to produce the solution. Users operating this program without a printer can follow the instructions given in Table 1-1 to enter data. The final answer is displayed and intermediate results are stored in data registers as shown in Table 1-3.

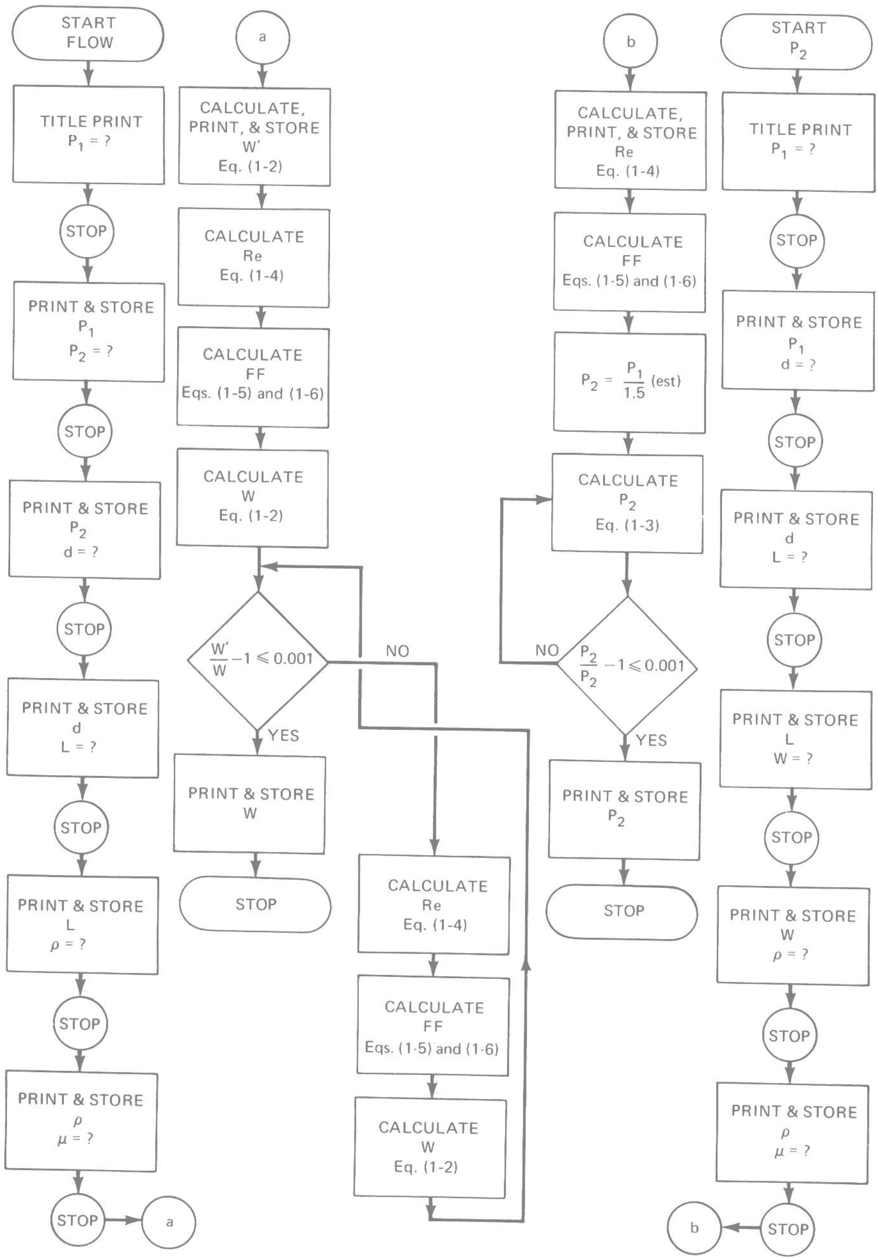

FIGURE 1-1 Compressible Isothermal Flow in Pipelines

TABLE 1-1 User Instructions

Step	Procedure	Enter	Press	Display
1	Partition calculator at 639.39	4	2d Op 17	639.39
2	Load program	Side 1		1
		Side 2		2
		Side 3		3
		Side 4		4
		ISOTHERMAL FLOW		
3	Press label A		A	2413007100
4		P_1	R/S	3303003336
5		p_2	R/S	7100000000
6		d	R/S	2700213700
7		L	R/S	6315210071
8		ρ	R/S	3300710000
9		μ	R/S	Flow, lb/h
		ISOTHERMAL ΔP		
3	Press label B		B	2413007100
4		P_1	R/S	7100000000
5		d	R/S	2700213700
6		L	R/S	2335007100
7		W	R/S	6315210071
8		ρ	R/S	3300710000
9		μ	R/S	P_2, psia
		IDEAL-GAS DENSITY		
3	Press label C		C	30430071
4		MW	R/S	330071
5		P	R/S	3765210071
6		T	R/S	ρ, lb/ft^3 or */CF

TABLE 1-2 User-Defined Keys

Label	Label Function
A	Calculates the maximum gas flow rate in pipelines for a given pipe size and pressure drop.
B	Calculates the terminal pressure in a given size pipeline with a known gas flow rate.
C	Calculates the ideal-gas density of a gas.

TABLE 1-3 Data Registers

Data register no.	Information stored	Units
00	Not used	
01	P_1	psia
02	P_2	psia
03	d	in
04	L	ft
05	W	lb/h
06	ρ	lb/ft³
07	μ	cP
08	$\frac{12L}{d}$	
09	$2 \ln \frac{P_1}{P_2}$	
10	$FF \frac{12L}{d}$	
11	Re	
12	FF	
13	0.00015(ε)*	ft
14	1337.024 (constant)*	
15	$d^4 \left(P_1^2 - P_2^2\right)\left(\frac{1}{P_1}\right)$	
16	0.013 (initial FF)*	
17	0.001 (tolerance)*	
18	P_1^2	
19	$W^2 (P_1)\left(\frac{1}{\rho_d^4}\right)$	
20	2436323723*	Print codes
21	1735301327*	
22	21273243*	
23	3302003336*	
24	2413007100*	
25	3303003336*	
26	1600243100*	
27	7100000000*	
28	2700213700*	
29	4300271463*	
30	2335007100*	
31	4224360015*	
32	3300710000*	
33	75330000*	
34	1631002714*	
35	6315210071*	

TABLE 1-3 Data Registers (Continued)

Data register no.	Information stored	Units
36	30430071*	↓
37	330071*	
38	3765210071*	
39	51631521*	

* Data which must be stored in data registers the first time the program is stepped into the calculator and before the program is stored on magnetic cards. Contents in registers 13, 16, and 17 may be varied by the user.

Examples

1. What is the maximum flow rate for a pipeline that is 100 miles (528,000 ft) long and has an internal diameter of 13.376 in? Gas enters the pipeline at 1300 psia and exits at 300 psia. The flowing gas has a density of 4.87 lb/ft^3 and a viscosity of 0.011 cP.
2. Assuming the same gas flow rate as Prob. 1, what is the gas pressure after 50 miles (264,000 ft)?
3. What is the ideal density of the gas at the end of the pipeline if the gas molecular weight is 20.1 and the flowing temperature is 40°F?

Procedure Press label A and answer the questions for solution 1, press label B and answer the questions for solution 2, and finally press label C and answer the questions for solution 3. After an answer to each question has been keyed into the calculator, the program is continued by pressing the R/S key.

Shown below are the solutions to these problems.

Solution 1 (label A)

```
ISOTHERMAL FLOW

P1 PSIA ?
        1300.
P2 PSIA ?
         300.
D IN ?
       13.376
L FT ?
      528000.
DN LB/CF ?
         4.87
VIS CP ?
        0.011
W LB/HR ?
  237117.6797
```

Solution 2 (label B)

```
ISOTHERMAL ΔP

P1 PSIA ?
        1300.
D IN ?
       13.376
L FT ?
      528000.
W LB/HR ?
  237117.6797
DN LB/CF ?
         4.87
VIS CP ?
        0.011
P2 PSIA ?
   300.001095
```

Solution 3 (label C)

```
   DN LB/CF ?

        MW ?
20.1
         P ?
300.
       T°F ?
40.
1.123951538     */CF
```

PROGRAM LISTING Compressible Isothermal Flow

000	76	LBL	047	99	PRT	094	43	RCL	141	42	STO
001	11	A	048	33	X^2	095	34	34	142	42	STO
002	69	OP	049	22	INV	096	69	OP	143	05	05
003	00	00	050	44	SUM	097	01	01	144	76	LBL
004	43	RCL	051	15	15	098	43	RCL	145	30	TAN
005	20	20	052	43	RCL	099	35	35	146	71	SBR
006	69	OP	053	01	01	100	69	OP	147	35	1/X
007	01	01	054	22	INV	101	02	02	148	71	SBR
008	43	RCL	055	49	PRD	102	69	OP	149	42	STO
009	21	21	056	15	15	103	05	05	150	48	EXC
010	69	OP	057	43	RCL	104	91	R/S	151	05	05
011	02	02	058	26	26	105	42	STO	152	55	÷
012	43	RCL	059	69	OP	106	06	06	153	43	RCL
013	22	22	060	01	01	107	99	PRT	154	05	05
014	69	OP	061	43	RCL	108	49	PRD	155	95	=
015	03	03	062	27	27	109	15	15	156	75	−
016	69	OP	063	69	OP	110	43	RCL	157	01	1
017	05	05	064	02	02	111	01	01	158	95	=
018	98	ADV	065	69	OP	112	55	÷	159	50	I×I
019	69	OP	066	05	05	113	43	RCL	160	32	X:T
020	00	00	067	91	R/S	114	02	02	161	43	RCL
021	43	RCL	068	42	STO	115	95	=	162	17	17
022	23	23	069	03	03	116	23	LNX	163	22	INV
023	69	OP	070	99	PRT	117	65	×	164	77	GE
024	01	01	071	33	X^2	118	02	2	165	30	TAN
025	43	RCL	072	33	X^2	119	95	=	166	43	RCL
026	24	24	073	49	PRD	120	42	STO	167	29	29
027	69	OP	074	15	15	121	09	09	168	69	OP
028	02	02	075	43	RCL	122	43	RCL	169	01	01
029	69	OP	076	28	28	123	31	31	170	43	RCL
030	05	05	077	69	OP	124	69	OP	171	30	30
031	91	R/S	078	01	01	125	01	01	172	69	OP
032	42	STO	079	69	OP	126	43	RCL	173	02	02
033	01	01	080	05	05	127	32	32	174	69	OP
034	99	PRT	081	91	R/S	128	69	OP	175	05	05
035	33	X^2	082	42	STO	129	02	02	176	43	RCL
036	42	STO	083	04	04	130	69	OP	177	05	05
037	15	15	084	99	PRT	131	05	05	178	99	PRT
038	43	RCL	085	65	×	132	91	R/S	179	98	ADV
039	25	25	086	01	1	133	42	STO	180	98	ADV
040	69	OP	087	02	2	134	07	07	181	91	R/S
041	01	01	088	55	÷	135	99	PRT	182	00	0
042	69	OP	089	43	RCL	136	43	RCL	183	00	0
043	05	05	090	03	03	137	16	16	184	00	0
044	91	R/S	091	95	=	138	42	STO	185	00	0
045	42	STO	092	42	STO	139	12	12	186	76	LBL
046	02	02	093	08	08	140	71	SBR	187	12	B

PROGRAM LISTING Compressible Isothermal Flow

188	69	OP	235	43	RCL	282	05	05	329	95	=
189	00	00	236	28	28	283	91	R/S	330	42	STO
190	43	RCL	237	69	OP	284	42	STO	331	10	10
191	20	20	238	01	01	285	07	07	332	43	RCL
192	69	OP	239	69	OP	286	99	PRT	333	01	01
193	01	01	240	05	05	287	43	RCL	334	55	÷
194	43	RCL	241	91	R/S	288	01	01	335	01	1
195	21	21	242	42	STO	289	33	X^2	336	93	.
196	69	OP	243	04	04	290	42	STO	337	05	5
197	02	02	244	99	PRT	291	18	18	338	95	=
198	43	RCL	245	43	RCL	292	43	RCL	339	42	STO
199	33	33	246	29	29	293	05	05	340	02	02
200	69	OP	247	69	OP	294	33	X^2	341	76	LBL
201	03	03	248	01	01	295	65	×	342	29	CP
202	69	OP	249	43	RCL	296	43	RCL	343	43	RCL
203	05	05	250	30	30	297	01	01	344	01	01
204	98	ADV	251	69	OP	298	55	÷	345	55	÷
205	69	OP	252	02	02	299	43	RCL	346	43	RCL
206	00	00	253	69	OP	300	06	06	347	02	02
207	43	RCL	254	05	05	301	55	÷	348	95	=
208	23	23	255	91	R/S	302	43	RCL	349	23	LNX
209	69	OP	256	42	STO	303	03	03	350	65	×
210	01	01	257	05	05	304	33	X^2	351	02	2
211	43	RCL	258	99	PRT	305	33	X^2	352	95	=
212	24	24	259	43	RCL	306	55	÷	353	85	+
213	69	OP	260	34	34	307	43	RCL	354	43	RCL
214	02	02	261	69	OP	308	14	14	355	10	10
215	69	OP	262	01	01	309	33	X^2	356	95	=
216	05	05	263	43	RCL	310	95	=	357	65	×
217	91	R/S	264	35	35	311	42	STO	358	43	RCL
218	42	STO	265	69	OP	312	19	19	359	19	19
219	01	01	266	02	02	313	43	RCL	360	95	=
220	99	PRT	267	69	OP	314	04	04	361	94	+/-
221	43	RCL	268	05	05	315	65	×	362	85	+
222	26	26	269	91	R/S	316	01	1	363	43	RCL
223	69	OP	270	42	STO	317	02	2	364	18	18
224	01	01	271	06	06	318	55	÷	365	95	=
225	43	RCL	272	99	PRT	319	43	RCL	366	34	$\sqrt{X}$
226	27	27	273	43	RCL	320	03	03	367	48	EXC
227	69	OP	274	31	31	321	95	=	368	02	02
228	02	02	275	69	OP	322	42	STO	369	55	÷
229	69	OP	276	01	01	323	08	08	370	43	RCL
230	05	05	277	43	RCL	324	71	SBR	371	02	02
231	91	R/S	278	32	32	325	35	1/X	372	75	-
232	42	STO	279	69	OP	326	65	×	373	01	1
233	03	03	280	02	02	327	43	RCL	374	95	=
234	99	PRT	281	69	OP	328	08	08	375	50	I×I

PROGRAM LISTING Compressible Isothermal Flow

Step	Code	Key
376	32	X:T
377	43	RCL
378	17	17
379	22	INV
380	77	GE
381	29	CP
382	43	RCL
383	25	25
384	69	OP
385	01	01
386	43	RCL
387	24	24
388	69	OP
389	02	02
390	69	OP
391	05	05
392	43	RCL
393	02	02
394	99	PRT
395	98	ADV
396	98	ADV
397	91	R/S
398	76	LBL
399	35	1/X
400	43	RCL
401	05	05
402	65	×
403	06	6
404	93	.
405	03	3
406	01	1
407	55	÷
408	43	RCL
409	03	03
410	55	÷
411	43	RCL
412	07	07
413	95	=
414	42	STO
415	11	11
416	32	X:T
417	02	2
418	00	0
419	00	0
420	00	0
421	22	INV
422	77	GE
423	25	CLR
424	06	6
425	04	4
426	55	÷
427	43	RCL
428	11	11
429	95	=
430	42	STO
431	12	12
432	76	LBL
433	25	CLR
434	07	7
435	55	÷
436	43	RCL
437	11	11
438	95	=
439	45	Y^X
440	93	.
441	09	9
442	95	=
443	85	+
444	03	3
445	93	.
446	02	2
447	04	4
448	65	×
449	43	RCL
450	13	13
451	55	÷
452	43	RCL
453	03	03
454	95	=
455	28	LOG
456	65	×
457	02	2
458	95	=
459	33	X^2
460	35	1/X
461	42	STO
462	12	12
463	92	RTN
464	76	LBL
465	42	STO
466	43	RCL
467	12	12
468	65	×
469	43	RCL
470	08	08
471	85	+
472	43	RCL
473	09	09
474	95	=
475	35	1/X
476	65	×
477	43	RCL
478	15	15
479	95	=
480	34	$\sqrt{X}$
481	65	×
482	43	RCL
483	14	14
484	95	=
485	92	RTN
486	76	LBL
487	13	C
488	69	OP
489	00	00
490	43	RCL
491	34	34
492	69	OP
493	02	02
494	43	RCL
495	35	35
496	69	OP
497	03	03
498	69	OP
499	05	05
500	98	ADV
501	69	OP
502	00	00
503	43	RCL
504	36	36
505	69	OP
506	03	03
507	69	OP
508	05	05
509	91	R/S
510	42	STO
511	06	06
512	99	PRT
513	69	OP
514	00	00
515	43	RCL
516	37	37
517	69	OP
518	03	03
519	69	OP
520	05	05
521	91	R/S
522	99	PRT
523	49	PRD
524	06	06
525	69	OP
526	00	00
527	43	RCL
528	38	38
529	69	OP
530	03	03
531	69	OP
532	05	05
533	91	R/S
534	99	PRT
535	85	+
536	04	4
537	06	6
538	00	0
539	95	=
540	65	×
541	01	1
542	00	0
543	93	.
544	07	7
545	03	3
546	95	=
547	22	INV
548	49	PRD
549	06	06
550	43	RCL
551	39	39
552	69	OP
553	04	04
554	43	RCL
555	06	06
556	69	OP
557	06	06
558	98	ADV
559	98	ADV
560	98	ADV
561	91	R/S