

INDEX

I.- AUTHOR'S EXPERIENCES – ENG. ALBERTO MTZ LLAURADO.

II.- ACKNOWLEDGMENT

III.- PROLOGUE

IV.- OBJECTIVES AND GOALS IN RELIABILITY FOR RECIPROCATING COMPRESSORS

- PART 2 –

SECTION 16.- RECIPROCATING COMPRESSORS IN PROCESS PLANTS WITH SEVERE SERVICES AND LIMITATIONS IN GAS EMISSIONS

LXV.- COMPRESSORS ARE HYDROGEN ‘COLOUR BLIND’

1.- HYDROGEN COMPRESSION BASICS

2.- DESIGN CONSIDERATIONS FOR RECIPROCATING COMPRESSORS

LXVI.- NET ZERO GOALS LIMIT OFFSHORE PROJECTS

1.- GROWTH OF LNG WORLDWIDE

2.- U.S. GULF COAST

LXVII.- RECIPROCATING COMPRESSORS FOR THE NATURAL GAS TREATMENT PLANT

1.- CAPITAL COSTS

2.- OPERATING COSTS

3.- AVAILABILITY

4.- OPERATING FLEXIBILITY

5.- CONCLUSION

LXVIII.- LESSONS LEARNED FROM THE USE OF A RECIPROCATING COMPRESSOR FOR CO2 INJECTION

1 INTRODUCTION

2 PLATFORM K12-B

3 COMPRESSOR DESIGN CHALLENGES

3.1 CO2 Compression

3.2 Pulsation study

3.3 Safety consideration

4 OPERATIONAL EXPERIENCES

5 ENHANCED GAS RECOVERY

6 UP-SCALING

7 CONCLUSION

LXIX.- CHALLENGES OF OXYGEN RECIPROCATING PISTON COMPRESSORS

1 INTRODUCTION

2 PISTONS

2.1 Pistons without Piston Rings

2.2 Pistons with Piston Rings

2.3 Conclusion of Piston Damages

3 PISTON ROD AND PISTON ROD PACKING

- 3.1 Piston Rod Damage
- 3.2 Piston Rod Packing
- 3.3 Piston Rod and Packing
- 4 INSPECTION AND MAINTENANCE
 - 4.1 Piston Rod Oil Detection
 - 4.2 Maintenance
 - 4.3 Inspection and Maintenance Conclusions
- 5 CONCLUSION

LXX.- BEST PRACTICE FOR EFFICIENCY AND EMISSIONS UPGRADES OF A GAS GATHERING COMPRESSOR

- 1 INTRODUCTION
- 2 DEN HELDER GAS TREATMENT PLANT
 - 2.1 Introduction
 - 2.2 Gas leakage from conventional packings
- 3 ZERO-EMISSIONS PACKING
 - 3.1 Principle of operation
 - 3.2 Gas leakage eliminated
 - 3.3 Experience with oil consumption
 - 3.4 The design evolves
- 4 NEW VALVES IMPROVE PERFORMANCE
 - 4.1 Issues with existing valves
 - 4.2 New valve design performs well
- 5.- CONCLUSIONS AND FUTURE PLANS

LXXI.- VIBRATIONS AT NATURAL GAS STORAGE FACILITIES DURING COMBINED OPERATION OF RECIPROCATING AND TURBO COMPRESSORS

LXXII.- SYSTEMS MOUNTING GUIDELINES FOR SEPARABLE RECIPROCATING COMPRESSORS IN PIPELINE SERVICE

- 1. INTRODUCTION
 - 1.1 INTRODUCTION
 - 1.2 SCOPE OF GUIDELINES
 - 1.3 DEFINITIONS AND TERMINOLOGY
 - 1.4 HISTORICAL PERSPECTIVE
 - 1.5 SITUATION SUMMARY
 - 1.6 TYPICAL PIPELINE COMPRESSOR APPLICATIONS
 - 1.7 RELEVANT CODES, STANDARDS, SPECIFICATIONS, AND GUIDELINES
- 2 BID SPECIFICATIONS
 - 2.1 PACKAGE CONFIGURATION REQUIREMENTS
 - 2.2 GENERAL REQUIREMENTS
 - 2.3 DESIGN ANALYSIS REQUIREMENTS
 - 2.4 SKID DESIGN REQUIREMENTS
 - 2.5 PIPING DESIGN REQUIREMENTS
 - 2.6 FOUNDATION DESIGN REQUIREMENTS
 - 2.7 INSTALLATION AND MOUNTING DESIGN REQUIREMENTS
 - 2.8 ALIGNMENT REQUIREMENTS
 - 2.9 INSTALLATION REQUIREMENTS
 - 2.10 START-UP AND OPERATION REQUIREMENTS
- 3 CHOOSING SKID OR BLOCK MOUNTING FOR MEDIUM AND HIGH-SPEED SEPARABLES
 - 3.1 SOME SKID MOUNT ADVANTAGES
 - 3.2 SOME SKID MOUNT DISADVANTAGES
 - 3.3 SOME BLOCK MOUNT ADVANTAGES
 - 3.4 SOME BLOCK MOUNT DISADVANTAGES
 - 3.5 THE CURRENT EXPERIENCE BASE FOR BLOCK MOUNTING

4 SKID DESIGN

4.1 BASIC REQUIREMENTS

4.2 SPECIFIC SKID DESIGN GUIDELINES

5 FOUNDATION DESIGN FOR A SKID MOUNTED COMPRESSOR

5.1 BASIC FOUNDATION REQUIREMENTS

5.2 SPECIFIC GUIDELINES FOR SKID MOUNT FOUNDATION DESIGN

6 FOUNDATION DESIGN FOR A BLOCK-MOUNTED COMPRESSOR AND ENGINE

6.1 BASIC REQUIREMENTS

6.2 SPECIFIC GUIDELINES FOR BLOCK-MOUNTED COMPRESSOR AND ENGINE

7 PIPING DESIGN AND DESIGN FOR PULSATION CONTROL

7.1 BASIC REQUIREMENTS

7.2 SPECIFIC GUIDELINES

8 DESIGN AND SPECIFICATION OF MOUNTING AND INSTALLATION

8.1 OVERVIEW AND BASIC REQUIREMENTS

8.2 SKID TO FOUNDATION MOUNTING

8.3 COMPRESSOR MOUNTING (TO SKID OR BLOCK)

8.4 DRIVER MOUNTING (TO SKID OR BLOCK)

8.5 CROSSHEAD GUIDE MOUNTING (TO SKID OR BLOCK)

8.6 CYLINDER HEAD END SUPPORT MOUNTING TO FOUNDATION (IF REQUIRED)

8.7 DISCHARGE BOTTLE TO FOUNDATION BLOCK MOUNTING

8.8 SUCTION BOTTLE STRUCTURAL SUPPORT MOUNTING: USE A GROUTED, ANCHOR BOLTED SUPPORT

8.9 VESSEL MOUNTING

9 ANALYTICAL STUDIES

9.1 OVERVIEW

9.2 PULSATION ANALYSIS

9.3 TORSIONAL ANALYSIS

9.4 PIPING AND COMPRESSOR MANIFOLD VIBRATION STUDY

9.5 STRUCTURAL ANALYSIS OF SKID AND MOUNTED COMPONENTS

9.6 FOUNDATION ANALYSIS

9.7 PIPING STRESS AND FLEXIBILITY ANALYSIS

9.9 INSTALLATION

9.9.1 BASIC REQUIREMENTS

9.9.2 GENERAL INSTALLATION GUIDELINES

9.9.3 FOUNDATION INSTALLATION

9.9.4 PREPARATIONS FOR GROUTING OF SKID TO THE CONCRETE

9.9.5 GROUTING

9.9.6 ALIGNMENT OF EQUIPMENT

9.9.7 INSTALLATION OF PULSATION BOTTLES AND PIPING

9.9.8 ENSURE PIPING AND ALL BOTTLE CHAMBERS ARE THOROUGHLY CLEAN BEFORE INSTALLATION AND OPERATION

9.10 START-UP AND COMMISSIONING

9.11 START-UP TESTING

9.12 CORRECTIVE ACTION FOR HIGH VIBRATION

9.13 LONGER TERM OPERATION

LXXIII.- VIBRATION AND PERFORMANCE DESIGN CONSIDERATIONS FOR MULTI UNIT RECIPROCATING COMPRESSOR GAS STORAGE FACILITIES

1. INTRODUCTION

2. A TYPICAL GAS STORAGE FACILITY

3. COMPRESSION EQUIPMENT (and some thoughts on each)

4. DESIGN STUDIES

5. TYPICAL RECOMMENDATIONS

6. ADDITIONAL CONSIDERATIONS

7. SUMMARY

LXXIV.- HYDROGEN USE IN THE REFINERY

TECHNOLOGY FOR KEROSENE, VACUUM GAS OIL, AND DIESEL HYDRO PROCESSING

LXXV.- ROOT CAUSE ANALYSIS OF A LONG TERM RELIABILITY PROBLEM WITH RECIPROCATING COMPRESSORS IN HYDROGEN SERVICE

- 1.- INTRODUCTION
- 2.- COMPRESSOR SYSTEM DESCRIPTION
- 3.- PROBLEM DESCRIPTION
- 4.- ROOT CAUSE ANALYSIS TEAM CHARTER
- 5.- ANALYSIS STRATEGY
- 6.- COMMON CAUSE ANALYSIS
- 7.- RECOMMENDATIONS
- 8.- ASSESSMENT OF RCA PROCESS RESULTS
- 9.- CLOSURE
- 10.- APPENDIX
 - 10.1.- DETAILS OF AN ALYSIS OF K-1927 FIRST STAGE VALVE FAILURE (APRIL 15, 1994)
 - 10.2.- PROBLEM STATEMENT
 - 10.3.- EVENT DESCRIPTION
 - 10.4.- PROBABLE CAUSES
 - 10.5.- HUMAN SYSTEM ISSUES
 - 10.6.- RECOMMENDATIONS

LXXVI.- RECIPROCATING AIR AND GAS COMPRESSORS

1. CYLINDER LUBRICATION
2. BEARING (RUNNING GEAR) LUBRICATION
 - B. Single- and Two-Stage Compressors
 1. Factors Affecting Cylinder Lubrication
 2. Factor Affecting Running Gear Lubrication
 - C. Multistage Compressors
 1. Factors Affecting Lubrication
 2. Lubricating Oil Recommendation

SECTION 17.- RELIABILITY IN PISTONS, PISTON RINGS, PISTON RODS, ROD PRESSURE PACKINGS, SEALS AND VALVES IN RECIPROCATING COMPRESSORS

LXXVII.- ESTABLISHING PISTON RING & RIDER BAND WEAR RATES

LXXVIII.- HIGH-PERFORMANCE PISTONS FOR RELIABLE RECIPS

LXXIX.- ASSESSING AND REDUCING LEAKS FROM RECIPROCATING COMPRESSOR SYSTEMS

LXXX.- SMART PACKING IN RECIPROCATING COMPRESSORS

LXXXI.- BETTER WITH BOTH: STASSKOL'S NEW SEAL BOASTS BETTER SEALING AND LONGEVITY

LXXXII.- A NEW DESIGN OF NON-COOLED PRESSURE PACKING FOR IMPROVED LIFE AND RELIABILITY

- 1 INTRODUCTION
 - 1.1 Water Cooling
- 2 THERMAL ANALYSIS OF PISTON ROD
 - 2.1 Frictional heating by packing
 - 2.2 Factors Affecting Generation of Frictional Heat
 - 2.3 Heat Flow Paths in the Packing Ring

- 2.4 One - dimensional heat flow model
- 3 DEVELOPMENT OF BOT PACKING RING
 - 3.1 Features of the new BOT design
 - 3.2 Testing the BOT ring design
 - 3.3 Ring Dynamics
- 4 THE "THERMOSLEEVE" NON-COOLED PACKING ASSEMBLY
- 5 FIELD TRIALS ON THE BOT RINGS AND THERMOSLEEVE PACKING
- 6 CONCLUSIONS

LXXXIII.- THE BCD PACKING RING – A NEW HIGH PERFORMANCE DESIGN

- 1 INTRODUCTION
- 2 FUNDAMENTAL INVESTIGATIONS
- 3 NEW BCD PACKING RING DESIGN
- 4 CONCLUSIONS

LXXXIV.- RECIPROCATING SEALING ELEMENTS - IMPORTANCE OF MATERIAL AND LAYOUT

- 1 INTRODUCTION
- 2 SEALING ELEMENT LAYOUT
- 3 SEALING ELEMENT MATERIAL
- 4 MATERIAL DEVELOPMENT
- 5 SUMMARY

LXXXV.- GENUINE NEW CONCEPT FOR A ZERO- EMISSION PACKING FOR RECIPROCATING COMPRESSORS

- 1 INTRODUCTION
- 2 THE NEW LEAK-FREE PACKING PRINCIPLE
- 3 SYSTEM LAYOUT AND CONFIGURATION
- 4 TEST RESULTS AND FIELD EXPERIENCE
- 5 CONCLUSIONS

LXXXVI.- LOW-FRICTION BUFFER SEALS FOR RECIPROCATING COMPRESSOR ROD PACKING

- 1. INTRODUCTION
- 2. SIDE-LOADED PACKING RINGS
- 3. AVAILABLE ALTERNATIVES TO TRADITIONAL SIDE-LOADED RINGS
- 4. SOLUTION – THE CARTRIDGE ASSEMBLY
- 5. CONCLUSION

LXXXVII.- RECIPROCATING COMPRESSORS : RELIABILITY IMPROVEMENTS FOCUSING ON COMPRESSOR VALVES, PISTON AND ROD SEALING TECHNOLOGY

- 1.- INTRODUCTION
- 2.- RELIABILITY ANALYSIS
 - 2.1.- Compressor Valves : the problem
 - 2.2.- Compressor Valves : the solution
 - 2.3.- Valve element design & material
 - 2.4.- Valve Dynamics Analysis
 - 2.5.- Field experience
 - 2.6.- Piston and Piston rod Sealing : the problem
 - 2.7.- Piston and Piston rod sealing : the solution
 - 2.8.- New Material Developments

- 2.9.- Oil lubricated applications
- 2.10.- Mating surface considerations

LXXXVIII.- RECIPROCATING COMPRESSORS : OPERATION AND MAINTENANCE

- 1.- COMPRESSOR PISTON ROD PACKING
- 2.- PACKING TYPES
- 3.- COOLED PACKING TYPE
- 4.- PACKING RINGS
- 5.- HOW COMPRESSOR PACKING WORKS
- 6.- PACKING RING TYPES
- 7.- PACKING RING SIDE CLEARANCE
- 8.- MAJOR SOURCES OF PACKING PROBLEMS
- 9.- PACKING PROBLEMS
- 10.- GARTER SPRING AND/OR RING BREAKAGE
- 11.- RATE OF LEAKAGE
- 12.- SERVICING PISTON ROD PACKING
- 13.- PISTON MOD OIL WIPER PACKING

LXXXIX.- RECIPROCATING COMPRESSORS – SEALING DESIGN

- 1 COMPRESSOR PACKING
- 2 BREAKER RINGS
- 3 PACKING RING TYPE BT
- 4 PACKING RING TYPE BD
- 5 COMMON PACKING RING CHARACTERISTICS
- 6 PACKING RING MATERIALS
- 7 LUBRICATED, SEMILUBRICATED AND NONLUBRICATED PACKING
- 8 PACKING RING TYPE TU
- 9 THERMAL EFFECTS
- 10 UNDERSIZED RODS
- 11 OVERSIZED RODS
- 12 TAPERED RODS
- 13 PACKING LEAKAGE
- 14 RING LEAKAGE AT LOW PRESSURE
- 15 PROBLEMS ASSOCIATED WITH LOW SUCTION PRESSURE
- 16 PROBLEMS ASSOCIATED WITH LOW LEAKAGE REQUIREMENTS
- 17 EFFECT OF RING TYPE ON LEAKAGE CONTROL
- 18 LEAKAGE CONTROL WITH DISTANCE PIECE VENTING
- 19 STATIC COMPRESSOR SEALING
- 20 COMPRESSOR BARRIER FLUID SYSTEMS FOR FUGITIVE EMISSIONS CONTROL
- 21 WIPER PACKING
- 22 HIGH PRESSURE (HYPER) PACKINGS
- 23 COMPRESSOR PISTON RINGS
- 24 COMPRESSOR RIDER RINGS
- 25 PISTON RING LEAKAGE
- 26 COMPRESSOR RING MATERIALS
- 27 SEAL RING FRICTION
- 28 COOLING RECIPROCATING COMPRESSOR PACKING

XC.- RECIPROCATING COMPRESSOR PISTON ROD PACKING

- 1 INTRODUCTION
- 2 EMISSION REDUCTION METHODS

XCI.- CONSIDER MODULAR REED VALVES FOR RECIPROCATING COMPRESSORS - TIPS FOR RELIABILITY PROFESSIONALS ENGAGED IN DUE DILIGENCE

1.- MODULAR REED VALVES

- 1.1.- Design considerations
- 1.2.- Examining modular reed valves
- 1.3.- Final thoughts

XCII.- RECENT DEVELOPMENTS, VALVE SELECTION, AND TECHNICAL ADVANCES

1 OVERVIEW

2 TYPES OF VALVES

3 EXAMINING MODULAR STRAIGHT-THROUGH FLOW VALVES

XCIII.- VALVES – TYPES (RECIPROCATING COMPRESSORS)

1.- DYNAMICS

2.- VOLUMETRIC EFFICIENCY

3.- COMPRESSION EFFICIENCY

4.- FINGER-TYPE SUCTION VALVE UNLOADER

XCIV.- NEXT-GENERATION COMPRESSOR VALVE TECHNOLOGY

1 INTRODUCTION

2 REQUIREMENTS TO BE MET BY MODERN COMPRESSOR VALVES

3 NEXT-GENERATION COMPRESSOR VALVE TECHNOLOGY FOR DEMANDING APPLICATIONS

3.1 Materials research

3.2 Manufacturing technology

3.3 Valve design

3.4 Challenges arising from capacity control systems

4 CASE STUDIES: THREE FIELD INSTALLATIONS

4.1 Reliable performance in a CCR regeneration loop compressor

4.2 Lower operating costs and higher efficiency in natural gas storage

4.3 Capital cost reduction for a refinery compressor

5 CONCLUSIONS

XCV.- A NOVEL POPPET VALVE DESIGN – THE ARROW-POPPET

1.- INTRODUCTION

2.- DESIGN CONCEPT

2.1.- General Design Considerations

2.2.- Arrowpoppet design

2.2.1.- Poppet

2.2.2.- Valve Guard

2.2.3.- Valve Seat

2.3.- Future Developments

- Closed design variant

- Bumpers

- Unloader

- Valve cartridge with unloader

- Valve cartridge with support

3.- DIMENSIONING AND CFD

3.2.- Comparison with other valve types

4.- EXAMPLES AND TEST RESULTS

4.1.- Compressor rests

4.2.- Field tests

5.- CONCLUSIONS

XCVI.- COMPRESSOR VALVES (RECIP. COMPRESSORS)

1 PURPOSE

2 HISTORY

3 SURVEY OF VALVE DESIGN

4 THEORY

4.1 Principle of operation

4.3 Motion of Sealing Element

4.4 Valve lift

4.5 Valve Areas

4.6 Valve Springs

4.7 Theoretical Valve Motion

5 VALVE MATERIALS

5.1 Valve Sealing Elements

5.2 Valve Springs

6 VALVE LIFE

7 METHODS TO VARY THE CAPACITY OF A COMPRESSOR

7.1 Clearance Volume Regulation

7.2 Fixed Volume, Variable Pressure Clearance Volume

7.3 Reverse Flow Capacity Control

7.4 Variable Speed Regulation

7.5 Bypass Control

7.6 Plug Unloaders

7.7 Valve Lifters

7.8 Valve Depressors (Unloaders)

7.9 Active Valves

XCVII.- TRIPLE-LAYERED DESIGN EXTENDS COMPRESSOR VALVE'S LIFE

SECTION 18.- RELIABILITY AND STRATEGIES IN LUBRICATION SYSTEMS APPLICABLE FOR RECIPROCATING COMPRESSORS

C.- FRAME LUBRICATION SYSTEM

1. OIL PRESSURE

2. OIL PRESSURE RELIEF VALVE

3. LOW OIL PRESSURE ALARM & SHUTDOWN PROTECTION

4. OIL FILTER

5. OIL COOLER

6. OIL TEMPERATURE

7. FRAME OIL CAPACITY

8. FRAME OIL SPECIFICATIONS

CI.- MQA TO DETERMINE BEST LUBRICATING STRATEGY FOR RECIPROCATING COMPRESSORS

1.- DESCRIBING MQA

2.- LUBRICANT APPLICATION

3.- CYLINDER LUBRICATION

CII.- CST CRAFTS PLS-100 LUBRICATION SYSTEM

1.- THE SYSTEM

2.- NOT A SINGLE PRODUCT

CIII.- ELIMINATING EXCESSIVE LUBRICATION

- 1. INTRODUCTION**
- 2. THE LUBRICATION SYSTEM**
- 3. COMPRESSOR LUBRICATION RATES**
- 4. EFFECTS OF OVER AND UNDER LUBRICATION**
- 5. THE IMPORTANCE OF MAINTAINING CONSISTENT LUBRICATION RATES**
- 6. SOLVING THE EXCESSIVE LUBRICATION PROBLEM**
- 7. CONCLUSION**

CIV.- NEW APPROACH FOR A SMART COMPRESSOR LUBRICATION SYSTEM

- 1 INTRODUCTION**
- 2 OLD AND NEW APPROACHES TO LUBRICATION**
 - 2.1 Current lubrication systems**
 - 2.2 Common-rail systems**
- 3. REQUIREMENTS FOR INJECTORS**
 - 3.1 Comparison of electric actuators**
 - 3.2 Piezoelectric actuators**
 - 3.3 Solenoids**
- 4. THE NEW SYSTEM IN DETAIL**
 - 4.1 System overview**
 - 4.2 injector solenoid**
 - 4.3 Embedded flow sensor**
 - 4.4 Integrated check valve**
 - 4.5 Temperature management**
 - 4.6 Two-wire installation**
 - 4.7 Control philosophy**
- 5. ENSURING RELIABILITY**
- 6. TESTING**
 - 6.1 Workshop tests**
 - 6.2 Compressor tests**
- 7. SYSTEMS COMPARISON**
- 8. SUMMARY AND OUTLOOK**

CV.- NOVEL OIL WIPER SYSTEM IN RECIPROCATING COMP.

- 1. INTRODUCTION**
- 2. TRADITIONAL OIL WIPER SYSTEMS**
- 3. COMBINATION OF OIL WIPERS WITH OTHER SYSTEMS**
- 4. INTRODUCING THE NOVEL OIL WIPER SYSTEM**
- 5. FIRST EXPERIMENTAL RESULTS**
- 6. SUMMARY**

CVI.- NEW CONCEPT LUBRICATION SYSTEM APPLICATION ON A HP RECIPROCATING COMPRESSOR

- 1 INTRODUCTION**
- 2 PROJECT SCENARIO**
- 3 THE NEW LUBRICATION SYSTEM IN DETAIL**
 - a. Basic principle overview**
 - b. Functional mechanical description**
 - c. Instrumentation and control logic**
- 4 START UP**
- 5 TESTING**

5.1 Bench preparation

5.2 Testing and solution of the first issue: divider block stall

5.3 Testing and solution of the second issue: pressure peaks

6 LESSON LEARNED

7 CONCLUSION

CVII.- COMPRESSOR CYLINDER LUBRICATION - CHARTS

CVIII.- DESIGN IN LUBRICATION FOR RECIPROCATING COMPRESSORS

1. INTRODUCTION

2. RECIPROCATING COMPRESSOR CRANKCASE

3 COMPRESSOR CYLINDERS

4 LUBE OIL SELECTION

5 OIL ADDITIVES

6 OPTIMUM LUBRICATION

7 OIL REMOVAL

8 NON-LUBE (NL) COMPRESSORS

9 SYNTHETIC LUBRICANTS

10 COMPRESSOR LUBRICATION EQUIPMENT

10.1 Pump-To-Point

10.2 Divider Block System

10.3 Cylinder Check Valves

10.4 Balancing Valves

10.5 Air Binding

CIX.- RELIABILITY IN COMPRESSOR LUBRICATION - XPERTLUBE

SECTION 19.- RELIABILITY IN DESIGN ABOUT THE MODULARIZATION, FOUNDATIONS, GROUTING, BASEPLATES & SKIDS FOR COMPRESSORS

CX.- GROUTING STYLES – IN COMPRESSORS

1. FULL-BED GROUTING

2. RAIL/SOLEPLATE GROUTING

3. EPOXY CHOCK GROUTING

4. GROUTING PREPARATION

5. MIXING AND POURING OF GROUT

6. CURING OF GROUT

7. TIGHTENING FOUNDATION BOLTS

8. COMPRESSOR INSTALLATION METHODS

9. FOUNDATION SIZE AND DESIGN

9.1. Foundation Construction

CXI.- COMPRESSOR FOUNDATION ASSESSMENT AND REPAIRS KEY TO REDUCING VIBRATIONS

1.- FOUNDATION DESIGN

2.- GROUT DESIGN/INSTALLATION

3.- ANCHOR BOLT DESIGN/INSTALLATION

4.- FOUNDATION ASSESSMENT

5.- VIBRATION

6.- VIBRATION ANALYSIS

7.- CASE STUDY

8.- SUMMARY

CXII.- AN ALTERNATIVE TO TRADITIONAL CONCRETE FOUNDATIONS

CXIII.- GROUT SYSTEMS FOR ROTATING AND RECIPROCATING MACHINERY

- 1.- PURPOSE OF GROUT
- 2.- MACHINERY FOUNDATIONS, ANCHOR BOLTS
- 3.- EPOXY GROUT
- 4.- EDGE LIFTING, CRACKS IN EPOXY GROUT
- 5.- GROUT FORMS AND POURING TECHNIQUES
- 6.- PUMPABLE EPOXY GROUTS

CXIV.- FOOT PRINT SIZE/WEIGHT/UNBALANCED FORCES/ FOUNDATIONS

CXV.- BEST PRACTICES IN COMPRESSOR MOUNTING

1 INTRODUCTION

2 BEST PRACTICES RELATED TO MITIGATING VIBRATION

- 2.1. Best Practices Related To the Construction of the Foundation
- 2.2. Best Practices Related to Epoxy Grout & Chocks
- 2.3. Best Practices Related to Anchor Bolts
- 2.4. Best Practices Related to Frame, Rail, Sole Plate and Foundation Preparation

3 BEST PRACTICES TO PREVENT FOUNDATION DEGRADATION

- 3.1. Best Practices Related To Foundation Design & Installation
- 3.2. Best Practices related to anchor bolts, nuts and washers
- 3.3. Best Practice Related To Anchor Bolt Holes / Sleeves / Covering / Sealing
- 3.4. Best Practices Related To Expansion Joints
- 3.5. Best Practices Related To Alignment Tools
- 3.6. Best Practices Related To Epoxy Grout & Chocks
- 3.7. Best Practices Related To Coating and Sealing the Foundation

4 ACKNOWLEDGEMENTS

5 CONCLUSION

CXVI.- RECIP FOUNDATIONS – PRACTICAL ISSUES RELATED TO INSPECTION AND REPAIR.

1. DESK INVESTIGATION

- 1.1 *As-built construction*
- 1.2 *Maintenance records*

2. FIELD INVESTIGATION

- 2.1 *Visual inspection (running compressor)*
- 2.2 *More comprehensive investigations (running compressor)*
- 2.3 *More comprehensive investigations (stopped compressor)*

3. ANALYSIS AND CORRECTION PLAN

- 3.1 *Repair methods*

4. PRACTICAL ISSUES DURING REPAIR

- 4.1 *3D positioning*
- 4.2 *Soleplates*
- 4.3 *Method of alignment*
- 4.4 *Anchoring*
- 4.5 *Grouting*
- 4.6 *Injection of cracks*
 - Cracks in the cement grout layer
 - Cracks in the foundation

CXVII.- DESIGN IN RECIPROCATING COMPRESSOR FOUNDATIONS

1 FOUNDATIONS

- 1.1 Types of Foundations**
- 1.2 Design**
- 1.3 Soil Frequency and Vibration**
- 1.4 Collection of Data for the Design Step***
- 1.5 Materials of Construction**
- 1.6 Anchor Bolts**
- 1.7 Support Systems**
- 1.8 Grout**
- 1.9 Repair of Foundations**

CXVIII.- SKID DESIGN AND ANALYSIS USING SOFTWARES

1 SKID DESIGN CHALLENGES

2 EXAMPLES OF SKID RESONANCE AND VIBRATION

3 SKID DESIGN SOLUTIONS

- 3.1 LIFTING, LOADING AND TRANSPORTATION STUDY – SCOPE AND FEATURES**
- 3.2 DYNAMIC SKID VIBRATION AND STRESS ANALYSIS – SCOPE AND FEATURES**

4 CUSTOMER BENEFITS

5 WOOD ADVANTAGES

CXIX.- STRUCTURAL VIBRATION AND DYNAMIC DESIGN ANALYSIS FOR FPSOS, PLATFORMS, ELEVATED STRUCTURES

1 OVERVIEW

2 SCOPE

3 FEATURES IN WOOD'S APPROACH AND CUSTOMER BENEFITS

- 3.1 FEATURES**
- 3.2 CUSTOMER BENEFITS**

4 WOOD ADVANTAGES

CXX.- MODULARIZED RECIPROCATING COMPRESSOR SYSTEMS AND THE FACTORS THAT INFLUENCE THEIR DESIGN

1 INTRODUCCION

2 HISTORY

3 PACKAGE SCOPE OF SUPPLY

3.1 COMPRESSOR SELECTION

- 3.1.1 Operating conditions and gas composition**
- 3.1.2 Capacity control**
- 3.1.3 Purge and vent systems**
- 3.1.4 Frame and cylinder lubrication**
- 3.1.5 Cylinder and packing cooling**
- 3.1.6 Process gas cooling**

3.2 DRIVER

- 3.2.1 Flywheel and coupling**

3.3 PULSATION AND VIBRATION CONTROL

- 3.3.1 Mechanical vibration analysis**
- 3.3.2 Pulsation studies**
- 3.3.3 Piping and vessels**

4 CONTROLS AND INSTRUMENTATION

5 INSTALLATION LOCATION

- a. Package design review**

6 ADVANTAGES AND DISADVANTAGES

7 CONCLUSION

8 ACKNOWLEDGEMENTS

CXXI.- DYNAMIC ANALYSIS OF RECIPROCATING COMPRESSORS ON FPSO TOPSIDE MODULES

- 1.- INTRODUCTION
- 2.- DYNAMIC STRUCTURAL ANALYSIS
- 3.- VIBRATION GUIDELINES FOR STRUCTURAL DYNAMIC ANALYSIS
- 4.- RECOMMENDATIONS

SECTION 20 .- STUDIES, SIMULATIONS AND ANALYSIS RELATED WITH RECIPROCATING COMPRESSOR / PIPING PULSATION AND VIBRATION AND TYPE OF SUPPORTS REQUIRED.

CXXII.- DATA NECESSARY FOR PULSATION ANALYSIS

CXXIII.- DRESSER-RAND DESIGN RECOMMENDATIONS FOR RECIPROCATING COMPRESSORS PIPING SYSTEMS

**CXXIV.- RECIPROCATING PRODUCTS – PULSATION ANALYTICS
CLAMP TYPE HOLD DOWN SUPPORT RECIPROCATING COMPRESSOR
APPLICATION**

– CASE STUDY IN A PROCESS PLANT (OIL REFINERY)

5 SUMMARY OF ACOUSTICAL ANALYSIS RESULTS AND PULSATION PLOTS

- 5.1 - 1st stage suction : Summary of results & plots
- 5.2 - 1st stage discharge : Summary of results & plots

CXXV.- MECHANICAL ANALYSIS

- CASE STUDY IN A PROCESS PLANT (OIL REFINERY)

1.0 SUMMARY

INTRODUCTION

2.0 PIPING DYNAMICS DESIGN GUIDELINES:

3.0 COMPRESSOR MANUFACTURER ENERGY PIPE CLAMP DRAWINGS

4.0 RECOMMENDED MAXIMUM PIPE CLAMP SPACING:

1st Stage Discharge System Mechanical Simulation Data

CXXVI.- TORSIONAL ANALYSIS REPORT

- CASE STUDY IN A PROCESS PLANT (OIL REFINERY)

1.- DISCUSSION

2.- CONCLUSION

3.- TORSIONAL ANALYSIS METHOD

4.- TORSIONAL VIBRATION ANALYSIS

5.- STEADY-STATE TORSIONAL RESPONSE

6.- APPENDIX-A --- MODE SHAPES

7.- APPENDIX-B --- CAMPBELL DIAGRAMS

8.- APPENDIX-C --- VIBRATORY STRESS PLOTS

9.- APPENDIX-D --- VIBRATORY TORQUE PLOT

10.- APPENDIX-E --- MOTOR SHAFT DRAWING

11.- APPENDIX-F --- COUPLING DRAWING

CXXVII.- NEW ADJUSTABLE VIBRATION ABSORBER

1.- USAGE OF VIBRATION ABSORBERS

2.- DESIGN OF THE MAGIC TUBE

3.- CASE STUDIES

4.- SECOND CASE STUDY

5.- CONCLUSION

CXXVIII.- APPLICATION OF A CONSTRAINED LAYER DAMPING TO REDUCE PIPE VIBRATIONS OF A RECIPROCATING COMPRESSOR SYSTEM

- 1.- INTRODUCTION
- 2.- SYSTEM DESCRIPTION
- 3.- CONSTRAINED LAYER DAMPING (CLD)
- 4.- TEMPERATURE EFFECT
- 5.- RESULTS
- 6.- CONCLUSIONS

CXXIX.- REDUCING PULSATIONS IN COMPRESSOR PIPING

- 1.- INTRODUCTION
- 2.- LESSONS LEARNED

CXXX.- PIPING VIBRATION AND INTEGRITY ASSESSMENT – SCOPE

- 1.- INTRODUCTION
- 2.- FRONT END ENGINEERING DESIGN (FEED) STAGE.
- 3.- WOOD ADVANTAGES
- 4.- SUMMARY

CXXXI.- PREVENTION OF PULSATION AND VIBRATION PROBLEMS IN ETHYLENE HYPERCOMPRESSOR SYSTEMS

1. INTRODUCTION
2. DSM LDPE PLANTS
 - 2.1 Introduction
 - 2.2 DSM recommendations in relation to pulsations and vibrations
 - 2.3 Experimental evaluation
3. PULSIM APPROACH IN THE DESIGN OF NEW-BUILD HYPER-COMPRESSOR PLANTS
 - 3.1 Development of PULSIM
 - 3.2 Our role as a co-designer
 - 3.3 Special problems in hyper-compressor Systems
4. SOME EXAMPLES OF A PULSATION AND MECHANICAL RESPONSE ANALYSIS FOR HYPER-COMPRESSORS
 - 4.1. The optimum location of orifice plates
 - 4.2 A combination of pulsation and mechanical response analysis to avoid unacceptable vibrations and cyclic stresses
5. CONCLUSIONS AND RECOMMENDATIONS

CXXXII.- MACHINERY-INDUCED PULSATIONS IN RECIPROCATING COMPRESSORS

- 1.- PULSATION DAMPENERS
- 2.- CYLINDER ORIFICE PLATES

CXXXIII.- EFFECT OF PULSATION BOTTLE DESIGN ON THE PERFORMANCE OF A MODERN LOW-SPEED GAS TRANSMISSION COMPRESSOR PISTON

- 1.- INTRODUCTION
- 2.- CASE STUDY 1
- 3.- SUMMARY

CXXXIV.- PULSATION AND VIBRATION CONTROL FOR RECIPROCATING COMPRESSORS

1.- ACOUSTICS / PULSATION CONTROL

- 1.1.- Purpose of an Acoustic Analysis**
- 1.2.- The Concept of Resonance – Acoustic vs. Mechanical**
- 1.3.- Helmholtz (Volume-Choke-Volume) Frequency**
- 1.4.- Check Layout for Potential Acoustic Resonance**

2.- FUNDAMENTALS OF PULSATION CONTROL

- 2.1.- Bottle Design Methodology**
- 2.2.- the Pulsation Bottle Sound Velocities $>2,000$ ft/sec**
- 2.3.- Size the Pulsation Bottle - Sound Velocities $\leq 2,000$ ft/sec**
- 2.4.- Acoustic Filter Characteristics**
- 2.5.- Acoustic Design Parameters**
- 2.6.- Acoustic Filter Design Goals**
- 2.7.- Two-Bottle Acoustic Filter Design – Low Speed**
- 2.8.- Two-Bottle Acoustic Filter Design – High Speed**
- 2.9.- Comparison of Two Bottle and Single Bottle Acoustic Filter Designs**
- 2.10.- Addressing Nozzle Resonance – A Significant Acoustic Resonance That Should Not Be Ignored During the Bottle Design**
- 2.11.- The Problem With Orifice Plates**
- 2.12.- Why Cylinder Nozzle Resonance Exists**
- 2.13.- Concept Behind the Virtual Orifice Technology**
- 2.14.- Basic Virtual Orifice Design**
- 2.15.- VO Field Testing at Boardwalk Pipeline Destin Station**
- 2.16.- VO – Destin Field Testing – Measured Pulsation Data (Discharge)**
- 2.17.- The Pressure Recovery Insert (PRI) Nozzle**
- 2.18.- Installation of PRI Suction Nozzle at El Paso Elk Basin Station**
- 2.19.- PRI Field Testing at El Paso Elk Basin Station**
- 2.20.- Nozzle Pulsations on 2nd Stage Discharge – Fully Load, Single tage Operation**
- 2.21.- Advanced Pulsation Control Conclusions**
- 2.22.- High Speed Bottle Design**
- 2.23.- Sizing the Cylinder Manifold Bottle**
- 2.24.- Sizing the Internal Choke Tubes**
- 2.25.- Internal Choke Arrangement**
- 2.26.- Finalize Bottle Design**
- 2.27.- Generate Bottle Drawing**
- 2.28.- Acoustic/Pulsation Analysis Summary**

3.- MECHANICAL DESIGN

- 3.1.- Mechanical Design of Reciprocating Compressors and Piping Systems**
- 3.2.- Mechanical Analysis of Compressors and Piping**
- 3.3.- Vibrations of Complex Systems**
- 3.4.- Piping Design for Vibration Control**
- 3.5.- Clamp Locations**
- 3.6.- Maximum Straight Span Lengths Between Effective Strap Type Restraints**
- 3.7.- Maximum Span Lengths Between Effective Strap Type Restraints For Spans with Elbows**
- 3.8.- Piping Layouts**
- 3.9.- Restraint Types and Stiffness**
- 3.10.- Effective Clamping**
- 3.11.- Clamp Installation and Maintenance #1**
- 3.12.- Elevated Piping**
- 3.13.- Compressor Manifold Systems**
- 3.14.- Mechanical Manifold Analysis**
- 3.15.- Modal Analysis**
- 3.16.- Sample Model Output**

- 3.17.- A Common Response: Suction Bottle Cantilever Mode
- 3.18.- A Common Response: Cylinder Mode
- 3.19.- A Common Response: Suction Piping Riser Mode
- 3.20.- Forced Response Calculations
- 3.21.- Mechanical Analysis – Typical Modifications
- 3.22.- Engineered Support Designs for Long Suction Bottles
- 3.23.- Supporting Discharge Bottles
- 3.24.- Cylinder Nozzles
- 3.25.- Repad Sizing
- 3.26.- Inspection Ports and Auxiliary
- 3.27.- Vertical Vessels
- 3.28.- Design Considerations for Internal Baffles & Chokes
- 3.29.- Baffle Loads
- 3.30.- Baffle Types
- 3.31.- Choke-Tube Mechanical Responses and “Tie-Downs”
- 3.32.- Unsupported Internal Chokes Can Fail
- 3.33.- Baffle and Choke Welding / Fabrication
- 4.- RECIPROCATING COMPRESSOR FIELD TESTING AND TROUBLESHOOTING
 - 4.1.- Field Testing
- 5.- PROCEDURE
- 6.- FIELD STUDY FUNDAMENTALS
- 7.- FIELD TESTING
- 8.- DATA ANALYSIS
 - 8.1.- Screening Piping Vibration Severity Chart
- 9.- PULSATION AND VIBRATION INSTRUMENTATION
 - 9.1.- Measuring Vibration
 - 9.2.- Measuring Pulsation
 - 9.3.- Measuring Strain
 - 9.4.- Data Acquisition System (DAS)
- 10.- PULSATION AND VIBRATION TEST POINTS
 - 10.1.- Dynamic Pulsation Data
 - 10.2.- Dynamic Strain and Vibration Data
 - 10.3.- Suction Bottle Bump Test
 - 10.4.- Temporary Wedges Placed to Support Suction Bottle
 - 10.5.- Strain Comparison with/without Temporary Wedges
- 11.- CONCLUSIONS
- 12.- CASE HISTORY #2
- 13.- FIELD STUDY SUMMARY

CXXXV.- THE EFFECT OF COMPRESSOR CYLINDER DESIGN ON NOZZLE PULSATIIONS:

- 1.- INTRODUCTION
- 2.- TEST RESULTS
- 3.- SUMMARY POINT

CXXXVI.- PULSATION AND VIBRATION CONTROL METHODOLOGY FOR HIGH-SPEED NATURAL GAS RECIPROCATING COMPRESSORS

- 1.- PULSATION CONTROL
- 2.- VIBRATION CONTROL

CXXXVII.- SPECIFICATION FOR RECIPROCATING COMPRESSOR PULSATION AND MECHANICAL VIBRATION ANALYSIS

- 1.- STEPS FOR SUCCESSFUL PROJECT
- 2.- PULSATION/VIBRATION STUDY REQUIREMENTS
- 3. MECHANICAL ANALYSIS

4. SKID
5. PIPING STRESS ANALYSIS (THERMAL/PIPING FLEXIBILITY ANALYSIS)
6. SMALL BORE CONNECTION (SBC) ASSESSMENT
7. FOUNDATION (OR STRUCTURE) DYNAMIC ANALYSIS

SECTION 21.- ROTORDYNAMICS ANALYSIS IN RECIPROCATING COMPRESSORS

CXXXVIII.- ROTORDYNAMICS ABOUT TORSIONAL AND LATERAL ANALYSIS IN RECIPROCATING COMPRESSORS

- 1.- TORSIONAL ROTORDYNAMICS
 - 1.1.- Steady-State Analysis
 - 1.2.- Allowable Stress Methodology for Torsional Systems
 - 1.3.- Torsional Damping
 - 1.4.- Forced Response Analysis
 - 1.5.- Transient Torsional Analysis
 - 1.6.- Testing Methods for Torsional Systems
- 2.- RECIPROCATING COMPRESSOR LATERAL ROTORDYNAMICS

CXXXIX.- TORSIONAL VIBRATION CASE STUDY HIGHLIGHTS DESIGN CONSIDERATIONS

- 1 INTRODUCTION
- 2 CASE HISTORY
 - 2.1 Original Design and Operation Resulting in Failures
 - 2.2 Post-Failure Design Audit
- 3 FIELD MEASUREMENTS AND DESIGN OF SOLUTION USING TUNED MODEL
- 4 PHILOSOPHY FOR DECIDING TO PERFORM A TORSIONAL DESIGN STUDY ON A NEW UNIT
- 5 CONCLUSIONS

CXL.- TORSIONAL ANALYSIS OF RECIPROCATING MACHINERY: DAMPING AND FORCED RESPONSE

- 1.- DAMPING ASSUMPTIONS